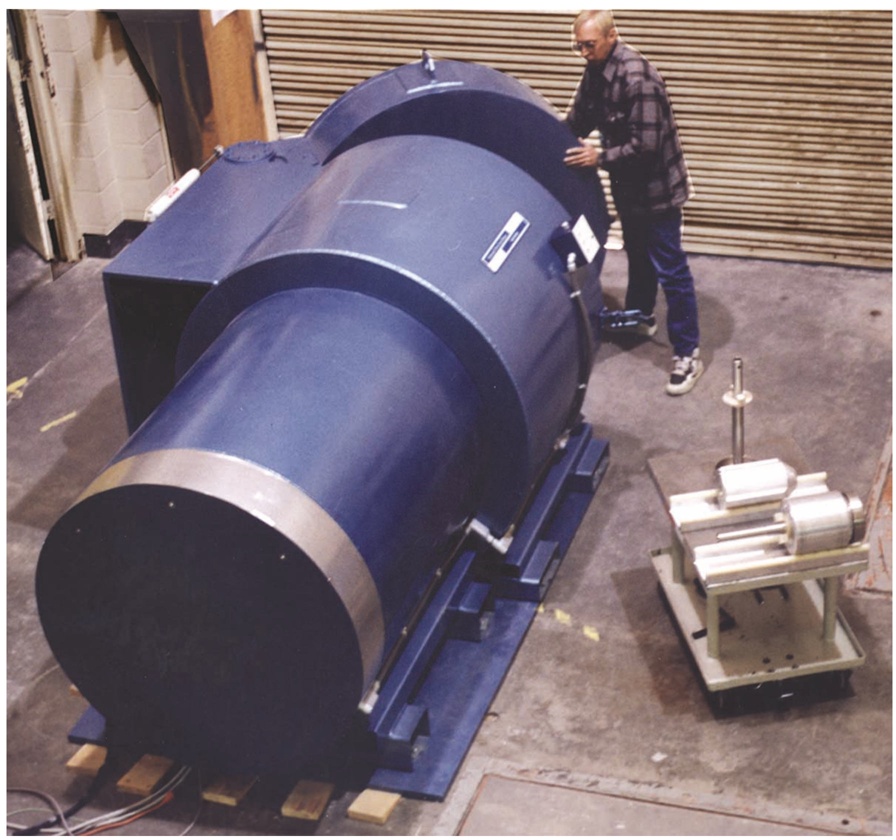
LA-13819-MS

Application Guide to Shufflers



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Cover photo: *Ed Adams opens the door to the Billet Shuffler's assay chamber. The large cylinder in the foreground stores the* ^{252}*Cf source. Two simulated billets are on the cart to the right.*

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Application Guide to Shufflers

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APPLICATION GUIDE TO SHUFFLERS

by

Phillip M. Rinard

ABSTRACT

This document is intended to serve as a comprehensive application guide to shufflers, a nondestructive assay (NDA) instrument that determines the fissile content of materials. Shufflers assay fissile materials by inducing fissions with neutrons from an isotopic source and counting the delayed neutrons. Shufflers were developed at Los Alamos National Laboratory (LANL) and are used throughout the Department of Energy (DOE) complex today. This guide is intended for users, potential users, and regulators of fissile materials. It describes the nature of shufflers and their performance in assaying fissile materials; source requirements; mechanical, electrical and software needs; performance, precision and accuracy; safety features; installation requirements; and operating procedures.

I. INTRODUCTION

A. The Purpose of this Application Guide

Shufflers were first conceived of in 1969 as a method to assay uranium masses nondestructively. About 20 shufflers have been built in the US, and several others have been built in France and the United Kingdom. This application guide will be useful to researchers who currently use shufflers, potential users who must choose a nondestructive assay (NDA) instrument for a specific need, or Department of Energy (DOE) regulators who want to understand the capabilities of NDA instruments. The DOE Office of Safeguards and Security is the sponsor of this guide.

For readers who want even more technical detail than what is presented here, several published reports are cited as references and can be used to supplement this guide. References 1–3 are especially recommended. The first two reports discuss the detailed theory behind shufflers, with applications used as illustrations. The third report is concerned with the shuffler design most widely used to assay 55-gallon drums (or smaller items) and discusses applications and results for assays of uranium and plutonium in a wide range of matrices. This application guide also includes an extensive bibliography of shuffler research at Los Alamos.

B. The Motivation for Shufflers

1. History of Shufflers

In the 1960s, the Los Alamos safeguards group, under the direction of G. R. Keepin, began assaying fissile materials using delayed neutrons released after irradiation by neutrons produced by D-T reactions in a Van de Graaff accelerator. The measurements of delayed neutron parameters by Keepin and others formed a strong basis for applying delayed neutrons to shuffler measurements.[4] When ^{252}Cf became available in the latter half of that decade, the advantages of using an intense isotopic source were quickly noted: reliable and predictable neutron source emission rate, simple maintenance, and neutron energies too low to stimulate (n,2n) and (n,p) reactions. The main disadvantage was also clear: ^{252}Cf must be shielded at all times because it cannot be turned off. A D-T accelerator is likely to be less expensive to purchase than a ^{252}Cf source, but considering operating costs there is no significant monetary difference between the accelerator and isotopic sources over their lifetimes.

Among the ^{252}Cf-based instruments proposed in 1969 was one in which a small capsule containing ^{252}Cf was "shuffled" pneumatically between storage and irradiation positions.[5] Fissions were induced in the fissile material and delayed neutrons counted after the ^{252}Cf source was returned to a shield. Figure 1 shows the "shuffling" process.

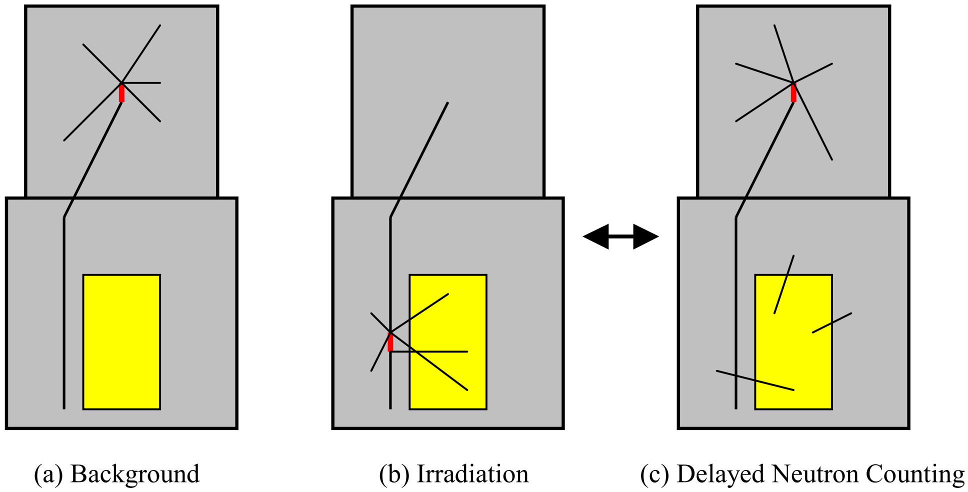


Fig. 1. The ^{252}Cf source alternates between the upper storage block and the lower assay chamber containing the object to be assayed (yellow). It is stored for the background count (a) and again stored after the irradiation (b) so that delayed neutrons can be counted (c) without the intense source present. Steps (b) and (c) can be repeated many times until the desired precision in the count is reached. This "shuffling" of the source between two positions gives rise to the name of the instrument. For this illustration the source should be scanned along the side of the object during the irradiation (b) while the object rotates. Detector tubes are not shown, but they surround the object to record the delayed neutrons in (c).

2. The Shuffler's Role Among Other NDA Instruments

Gamma-ray-based instruments perform excellent assays on uranium and plutonium materials of limited size. Gamma rays are more readily attenuated than neutrons, so even with good attenuation corrections there soon comes a point where the attenuation is too large and assays are no longer accurate. Before this point is reached, plutonium materials are emitting enough neutrons per second through spontaneous fissions to make passive neutron counting feasible. Total neutron, coincidence neutron, and neutron multiplicity counters have evolved to provide increasingly accurate assays of bulk plutonium. The shuffler technique usually does not compete with these passive counters because the neutrons from spontaneous fissions become a hindering background for a shuffler instead of the signal on which an assay is based with a passive instrument; several exceptions will be noted later.

However, uranium's passive emission of neutrons is far weaker than plutonium's and passive counters are inadequate for all but large masses (> 1 kg) of ^{238}U. Active well coincidence counters (AWCCs) were developed for uranium assays and their use overlaps some shuffler applications. An AWCC has AmLi sources of neutrons placed above and below a can-sized container of uranium. Neutrons from the AmLi sources induce fissions and the fission neutrons are distinguished from the AmLi neutrons through their correlations in time (multiple neutrons are emitted from a fission; AmLi neutrons are singly produced). The AmLi neutrons that directly reach the detectors from the AmLi sources generate a high background rate that limits the precision (and sensitivity or minimum detectable mass) of the instrument.

An obvious NDA niche for shufflers is in high-precision assays of bulk uranium where gamma-ray instruments cannot be used. Bulky items can be assayed with neutrons where gamma rays are strongly attenuated. The precision is better than with an AWCC because the shuffler's background rate during the count is very low. Since this initial application, the use of shufflers has expanded to other circumstances. Some applications simply compete with other instruments, but others are unique to shufflers.

For instance, a shuffler for bulk uranium can be used as a passive counter for bulk plutonium, simply by keeping the ^{252}Cf source inside its shield while a passive count is taken. The shuffler's assay chamber can be designed to meet the criteria for passive counters, and one instrument then serves two roles. This application guide merely notes this passive capability; an application guide to passive neutron multiplicity counting already exists.[6]

3. Applications of Los Alamos Shufflers

This overview begins with an application for which Los Alamos shufflers are uniquely qualified: assaying large masses of dense uranium metal and oxide. Two variants of a shuffler for 55-gallon drums are described, with applications to both large uranium masses and small waste quantities in waste containers. Shufflers for unusual applications are also described. In these cases, high gamma-ray background rates or interference by neutrons from plutonium or curium make using a shuffler necessary, instead of another instrument. Extensive details on all of these shufflers can be found in the references listed in the bibliography.

Figure 2 shows the geographical distribution of existing Los Alamos shufflers throughout the DOE complex and at the Dounreay Reprocessing Plant in Scotland. Shufflers produced domestically in the UK and France are not shown.

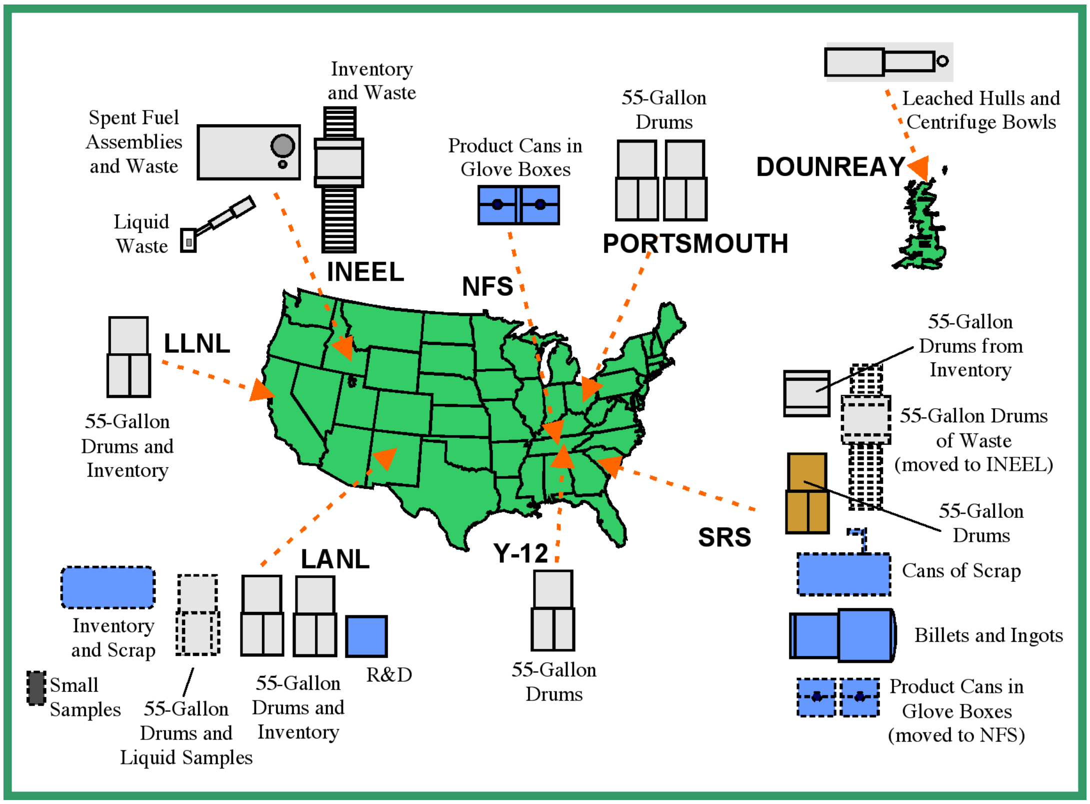


Fig. 2. Shufflers developed at Los Alamos are located at these DOE sites and in Scotland. The diagrams of the shufflers approximate their appearances and the notes indicate their applications.

a. Bathtub Shuffler

The first shuffler (Fig. 3), which was made in 1975, was dubbed the "bathtub" because of its general appearance. It could assay uranium in a wide range of forms because of its many features. Separate storage and irradiation "tanks" on wheels allowed assays on small containers, large drums, and fuel elements. The joint between these two tanks is hidden behind the electronics rack in Fig. 3. This shuffler was also used on inventory samples, scrap, waste, uranium ore, irradiated fuel, and mixed-oxide (MOX) fuel. The ^{252}Cf source was attached to a strong, flexible steel cable and driven by a fast, precise stepping motor. Spectrum tailoring by metals surrounding the ^{252}Cf source was done to prevent fissioning in ^{238}U. Thermal neutrons could also be used for the irradiation by changing the tailoring materials. Passive and active measurements with the same shuffler were combined to assay MOX materials.

Fig. 3. Mel Stevens opens the assay chamber of the Bathtub Shuffler, partially hidden by the electronics rack. Computers that could easily control the instrument and the assay process were not available in 1975. Howard Menlove and Tom Crane led this shuffler project.

b. Savannah River Uranium Scrap Shuffler

A similar but less-versatile shuffler (Fig. 4) was built for the Savannah River Site (SRS) in 1978 specifically for assaying the mass of ^{235}U in cans of scrap metal from the billet extrusion process of making production fuel assemblies (Building 321-M). This usually involved kilogram quantities of uranium metal with enrichments from 50% to 80%. The spectrum-tailoring feature was retained to avoid interference from fissions in ^{238}U.

Gamma rays could not be applied to these bulk materials and the AWCC had just been developed, but not yet fielded. The only practical instrument was the shuffler, and its precision gave it an advantage over an AWCC.

Fig. 4. The Uranium Scrap Shuffler featured a hoist to raise and lower the heavy cans of scrap. A computer in an air-conditioned electronics rack was used to control the instrument and perform the data analysis. Tom Crane led this project.

c. Savannah River Billet Shuffler

The Billet Shuffler (Fig. 5), installed at Savannah River in 1992, complemented the Uranium Scrap Shuffler and was installed near it in Building 321-M. The Billet Shuffler determined the ^{235}U contents in billets prior to their extrusion into fuel tubes. It was important to know the ^{235}U mass accurately to properly load the production reactors with fuel.

This shuffler had a delayed neutron count precision of 0.25% (1σ) and an accuracy of 0.5% (1σ), even though the assay time (including a background count) was only 10 minutes. Such a performance was made possible by the large ^{235}U loading of a billet (typically 1.7 kg) and the hollow core through a billet. A relatively small ^{252}Cf source (30 to 60 µg) was shuffled into and out of the center of the billet, making unusually efficient use of the irradiating neutrons. The excellent accuracy was made possible by the creation and careful characterization of a set of calibration billets provided by Savannah River.

After the shutdown of the production reactors, the Billet Shuffler was used to measure uranium ingots prior to their shipment to Oak Ridge National Laboratory (ORNL). It assayed thousands of uranium ingots that previously would have become billets. The Billet Shuffler was then moved to a reactor building in K Area to assist in the building's decommissioning.

Fig. 5. Ed Adams opens the door to the assay chamber of the Billet Shuffler. The large cylinder in the foreground stores the ^{252}Cf source. Two simulated billets are on the cart to the right. The electronics rack and computer are not shown. Phil Rinard led this project.

d. Savannah River Product Oxide Shufflers

A pair of identical shufflers (Fig. 6) was made in 1984 to fit around wells projecting from the bottoms of glove boxes in the Naval Materials Facility at Savannah River. Cans of product oxide could be lowered into the wells and assayed with the shufflers. Great care was taken to reach the best possible precision and accuracy, resulting in an accuracy of 0.36% (1σ). This was accomplished with 100 μg of ^{252}Cf in 1000 s (including a 300-s background).

After Savannah River had no further programmatic need for these shufflers, they were transferred to Nuclear Fuel Services, Inc., in Tennessee, to serve the same purpose.

Fig. 6. One of a pair of identical Product Oxide Shufflers. The assay chamber is behind the blue panel that slides under a glove box, simulated here at Los Alamos during development. A cylindrical well in the glove box floor holds a can of uranium oxide during a measurement. The short electronics racks flanking the assay chamber also fit under the glove box. Norbert Ensslin and Tom Crane led this project.

e. The "Standard" 55-Gallon-Drum Shuffler and Its Predecessors

There has been an evolutionary progress in shufflers designed for 55-gallon-drum containers. In the late 1970s, a prototype shuffler for 55-gallon drums was created at Los Alamos by taking a passive neutron counter and adding a ^{252}Cf storage block and assorted electronics. It was used to gain experience with 55-gallon drum assays and other materials. Years later it was moved to Los Alamos's Chemistry and Metallurgy Research (CMR) Building to fill a temporary need and then was scraped. A unique feature of the shuffler was the shielding material in the walls of the assay chamber: water.

This type of shuffler was redesigned for Savannah River in 1984 to measure the uranium masses from fractions of a gram to hundreds of grams in 55-gallon waste drums with assorted matrices (Fig. 7). Flux monitors were included to correct for variations in matrix effects. These were two low-efficiency ^{3}He tubes that counted while the intense ^{252}Cf source irradiated a drum. One of the tubes was wrapped in cadmium so that moderators in a drum would affect the ratio of counts from these tubes. As a drum rotated on a turntable, the ^{252}Cf source scanned vertically to produce a distribution of delayed neutron precursors proportional to the distribution of uranium.

The shuffler was partially redesigned for the Portsmouth Gaseous Diffusion Plant to take advantage of improvements in electronics and ^{252}Cf motion control. Two of these shufflers (Fig. 8) were delivered to Portsmouth in 1989 and 1991. Los Alamos commercialized this shuffler with Canberra Industries of Meriden, Connecticut, which has since built two models for Los Alamos, one for Lawrence Livermore National Laboratory, and one for the Y-12 Plant at Oak Ridge. The applications of these shufflers have reached well beyond waste quantities to miscellaneous inventory items (grams to many kilograms of ^{235}U, ^{233}U, and ^{237}Np). The design in Fig. 8 is now the "standard" 55-gallon-drum shuffler.

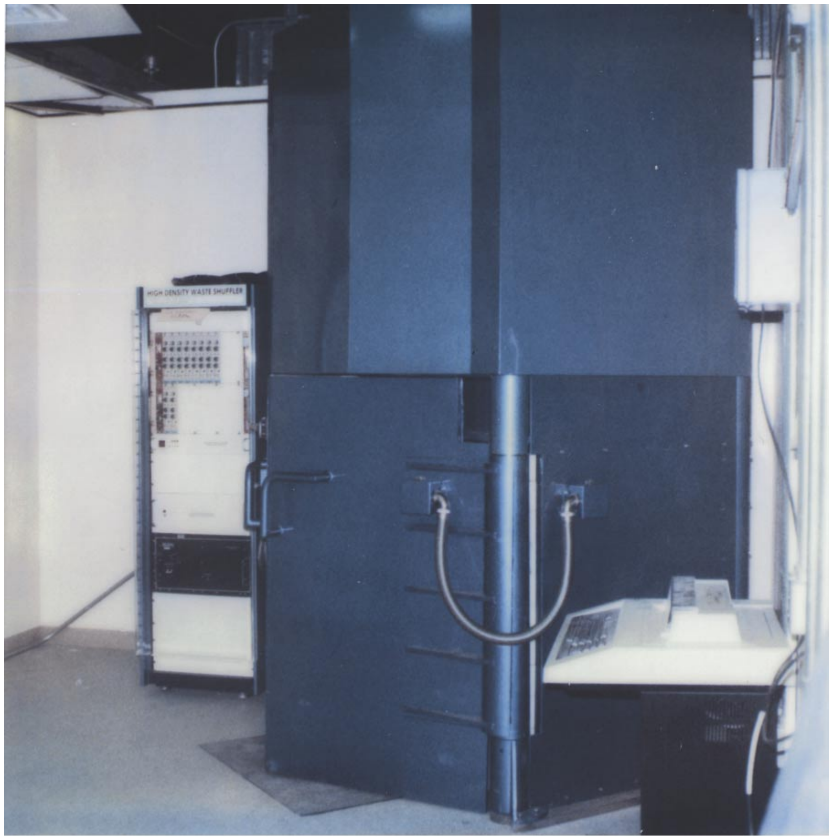


Fig. 7. The first shuffler fielded for 55-gallon drums was this one at Savannah River. The body of the shuffler is seen from the side, with the doors on the left. The upper half is a storage block for the ^{252}Cf source. A pit containing a bank of neutron detectors and a turntable rotation mechanism are located under the assay chamber and below the floor level. Norbert Ensslin and Tom Crane led this project.

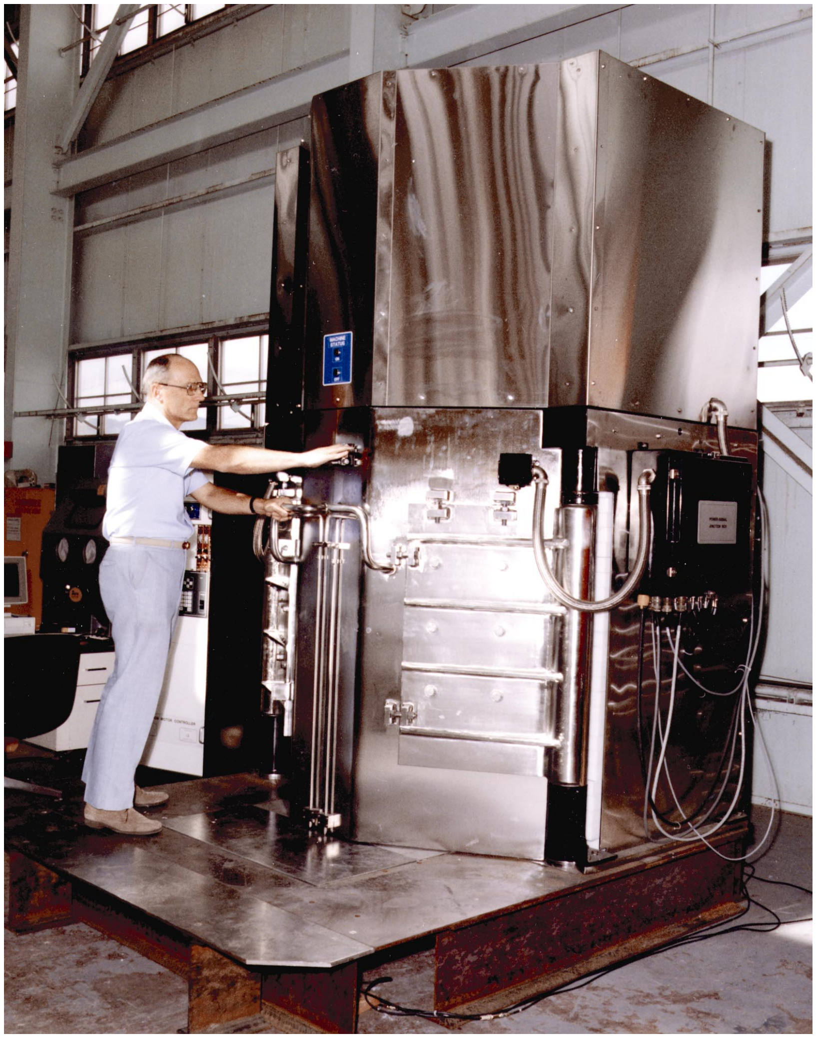
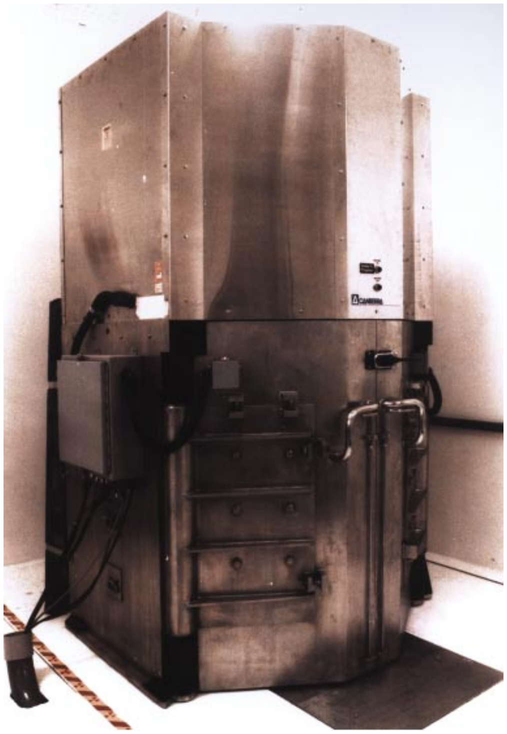


Fig. 8. Phil Rinard prepares to open the doors of the successor to the shuffler shown in Fig. 7. Before shipping to Portsmouth, it was assembled and tested at Los Alamos on a 1-ft.-high riser. After installation, it sat flush with the floor, as shown in Fig. 7. This design was commercialized through Canberra Industries. Howard Menlove, Jim Sprinkle, and Phil Rinard led this project.

The shuffler at Los Alamos's CMR Building (Fig. 9) is a commercial version of the one shown in Fig. 8. It assays drums and cans of waste, oxides, and assorted inventory items. After installation, it was modified to perform assays with a correction for the uranium distribution throughout a drum in addition to doing the conventional assays.[7] A stepping motor replaced the analog motor of the turntable and new software controlled the new data collection procedure and did the data analysis. The shuffler at Los Alamos's Plutonium Processing Facility (TA-55, PF-4) (Fig. 10) is identical to shuffler in the CMR Building (Fig. 9). The routine applications are much the same as with the CMR shuffler, but it has also been used for a unique application: measuring the plutonium content in cans of pyrochemical salt. The residual plutonium is usually in small pellets distributed within the salt. Gamma-ray techniques are commonly applied, but when the pellets exceed a certain size the self-attenuation is too large for the gamma rays. Passive neutron techniques generally fail because there is an intense neutron background rate from (α,n) reactions within the salt. The shuffler has shown that it can override this neutron background and generate a useful signal. Pellets that are too attenuating for gamma rays are hardly attenuating at all for neutrons; high background rates that prevent passive counting also limit the precision of a shuffler count, but do not make it impossible.



(a)

(b)

Fig. 9. The shuffler for 55-gallon drums installed in Los Alamos's CMR Building. Figure 9(a) shows the shuffler installed flush with the floor; the floor of the assay chamber is level with the room's floor because there is a one-foot-deep pit below the assay chamber to hold the turntable and a detector bank. Figure 9(b) shows three Los Alamos shuffler users in front of the CMR shuffler. From left to right are Jon Hurd (principal user of the similar shuffler at PF-4), Faye Hsue (principal user of the CMR shuffler), and Cippie Gomez (technician for the CMR shuffler).

Fig. 10. Sandra Hildner opens the doors of the shuffler for 55-gallon drums at the Los Alamos Plutonium Facility (TA-55) to reveal a 55-gallon drum. There is a basement below this room, so a one-foot-deep pit for the turntable and detector bank could not be made. Instead, the shuffler is installed on a one-foot-high platform and heavy items are lifted with a mechanical assist.

f. The "Pass-Through" 55-Gallon-Drum and Boxed-Waste Shufflers

Savannah River requested two shufflers for 55-gallon waste drums and boxed waste that could reside on materials accountability boundaries and decide, on the basis of an assay, whether a drum or box was allowed outside the boundary. A container inside the boundary entered the input door of the shuffler and was measured. If the uranium mass was below a preset limit, the output door opened and the container was now outside the boundary. Otherwise, the input door reopened and the container was kept within the boundary. This automated process avoided the costs of having to repeatedly open a boundary and use guards to check people in and out.

One of these shufflers had a conveyor system (Figs. 11 and 12) that ran through the shuffler and moved the containers automatically. The other shuffler (Fig. 13) required operators to move the drums, but the doors were controlled by the shuffler's software.

The shuffler with the conveyor was installed in Building 321-M in 1993, not far from the Scrap and Billet shufflers. After the production reactors were shut down and fuel tube production ceased, the shuffler with a conveyor was adopted by Argonne National Laboratory at the Idaho National Engineering and Environmental Laboratory (INEEL).

The shuffler without a conveyor was originally destined for Building 221-H, but programmatic changes led it to a different destiny, which is described in the next section.

Fig. 11. The input side of the Pass-Through Shuffler is shown with its conveyor system. At Savannah River, the rollers of the conveyor were flush with the floor. Chris Bjork (shown at the electronics rack) led the Pass-Through Shuffler projects.

Fig. 12. The output side of the shuffler has a longer conveyer section to allow containers to be stored while new containers are assayed. Shown here are 55-gallon drums, a HEPA filter, and a cardboard box. The conveyor system automatically centered all objects in the assay chamber.

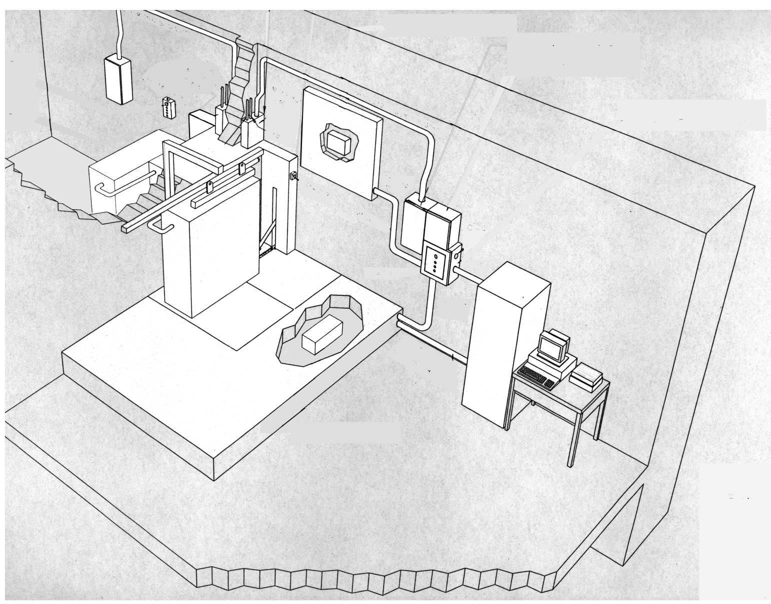


Fig. 13. The Pass-Through Shuffler for Building 221-H at Savannah River is shown as it was to be installed originally. The shuffler is on both sides of the cutaway wall. The two doors are shown in the upper-left quadrant in partially open states. Between them, at the junction of the walls, is the assay chamber. The turntable rotation motor is shown as a box in a cutaway section of the base for the shuffler. The electronics rack and computer are shown on the right side of the drawing. Assorted support electronics are mounted on the wall, some of which were for security purposes.

g. Mixed Fissile Materials

The Pass-Through Shuffler for Building 221-H at Savannah River was adapted in 1996 for a new application in Building 235-F (Fig. 14) where there is an old inventory of uranium and plutonium materials still in the original shipping containers. Although the shuffler was not designed for passive multiplicity counting, it proved to be adequate (but not ideal) for that technique, and this analysis made it possible to do accurate plutonium assays despite the presence of important impurities. An add-a-source (^{252}Cf) mechanism was retrofitted onto the shuffler to assist with matrix corrections of the passive measurements, if needed. This add-a-source was necessarily much weaker than the shuffler's normal ^{252}Cf source. The shuffler's flux monitors were also used to watch for variations in matrix effects; fortunately, there were none because the packaging was uniform.

The active mode of the shuffler was also used on the containers to obtain uranium mass, but when plutonium and uranium were both present, a correction had to be made to the measured count rate for the plutonium contribution. By studying these mixtures of materials, researchers gained extensive experience in the measurement process and data analyses of gamma rays, passive neutrons, and active neutrons.

The shuffler remains in Building 235-F performing measurements on various inventory items.

Fig. 14. The Pass-Through Shuffler without a conveyor system was adapted for use as a single-door shuffler and also as a multiplicity passive counter with add-a-source matrix correction capability. It is shown installed at Savannah River beside its electronics rack. Chris Bjork and Phil Rinard led this effort.

h. Compact UF_6 Sample Shuffler

In about 1985, the smallest Los Alamos shuffler was built to assay small samples of UF_6 (Fig. 15). The body of the shuffler was made of portions of two 55-gallon drums; the shuffler had the diameter of a 55-gallon drum but was about 50% taller. The ^{252}Cf source could be brought very near the small UF_6 sample, so the source did not have to be very strong and the shielding needed was slight.

Fig. 15. Dave Garcia adjusts the UF_6 Sample Shuffler, designed by Howard Menlove. What appears to be a 55-gallon drum is actually the body of the shuffler. A programmable calculator was used to perform the data collection and analysis.

i. Spent Naval Fuel Shuffler

At the opposite extreme in size of the Compact UF_6 Sample Shuffler is the Spent Naval Fuel Shuffler (Fig. 16). This shuffler, also known as the Fluorinel and Storage (FAST) Facility Shuffler, measured the uranium content in a spent fuel assembly prior to reprocessing. The intense gamma rays from fission products made it impossible to use gamma rays from uranium to form an assay. In commercial reactor low-enriched spent fuel, the buildup of ^{244}Cm creates an intense passive neutron emission rate that prevents a shuffler from detecting the much weaker signal of delayed neutrons from uranium (and also prevents passive counting for plutonium). But in highly enriched naval fuel, the ^{244}Cm buildup is much smaller, so this shuffler could perform neutron assays for uranium directly. It required a 1- to 3-mg ^{252}Cf source, which is larger than usual for shufflers but not unusual in other industrial applications of ^{252}Cf. The shuffler was built for the Idaho Chemical Processing Plant (ICPP), now known as the Idaho Nuclear Technology and Engineering Center (INTEC).

Because the spent fuel had to remain within the shielding of a hot cell, the shuffler's body had to remain inside the hot cell. Nevertheless, a large neutron shield was necessary to hold the ^{252}Cf source when it wasn't irradiating a fuel assembly and to protect workers who might have to enter the shuffler's general area. The ^{3}He tubes were shielded from the fission products' gamma rays by 4 inches of lead. An assembly was moved vertically at a steady rate through a penetration through the shuffler's body. The ^{252}Cf source performed its series of shuffles on the various segments of the fuel as they moved through the shuffler. In effect, the source scanned the length of the fuel, but the fuel did the vertical scanning. The shuffler was designed to control and coordinate the hoist moving the fuel, but the manually operated hoist was never replaced with an automated model. Nevertheless, the shuffler became part of the reprocessing operations and proved to be very accurate.

A second, smaller tube passing through the shuffler's body was provided to assay canisters of waste using the same ^{252}Cf source, but this capability was never applied.

Fig. 16. Project leader George Eccleston (left) and Tom Van Lyssel assemble the Spent Naval Fuel Shuffler for testing at Los Alamos. A container is suspended above a small tube where assays are done on waste material inside the container. A larger tube to the left is for the fuel assemblies. A motor in the center of the photograph could run an automated hoist. The motor at the bottom of the photograph is the stepping motor for the ^{252}Cf *source.*

j. Liquid Raffinate Shuffler

A much smaller shuffler was devised for the ICPP to monitor the concentration of uranium in a liquid raffinate stream (Fig. 17). The liquid was on its way to a storage tank and the ^{235}U concentration had to be controlled to avoid criticality problems in the tank. This shuffler was designed to measure the concentration every 100 s and generate a warning if the concentration exceeded 0.034 g-^{235}U/L and an alarm if it exceeded 0.48g-^{235}U/L. The flow rate could be anywhere between 0 and 102 L/h, with 60 to 100 L/h most likely. A higher flow rate reduced the delayed neutron count rate (more precursors are flushed out) so a flow rate meter on the facility's pipe sent measured rates to the shuffler's computer where a correction for deviations from the nominal rate of 80 L/h were made.

Because the raffinate contained fission products, the gamma-ray intensity was high. The pipe around which the shuffler sat was on the wall of a large hot cell. The pipe was cut so that the assay chamber could be inserted. The chamber was a hollow cylinder that held about 2 liters of the liquid at a time. The ^{252}Cf source could be brought into the hollow center and efficiently irradiate the liquid. Only about 30 μg of ^{252}Cf was required because of this favorable geometry and the moderation by the liquid. Fissions were induced by thermal neutrons and the probability of fission is much greater than with higher-energy neutrons.

The shuffler was fabricated and tested in a hot cell at Los Alamos. The raffinate was simulated by nitric acid solutions containing different uranium concentrations. The shuffler was installed at the ICPP in 1991 but never placed in operation because the end of the cold war brought reprocessing to a halt.

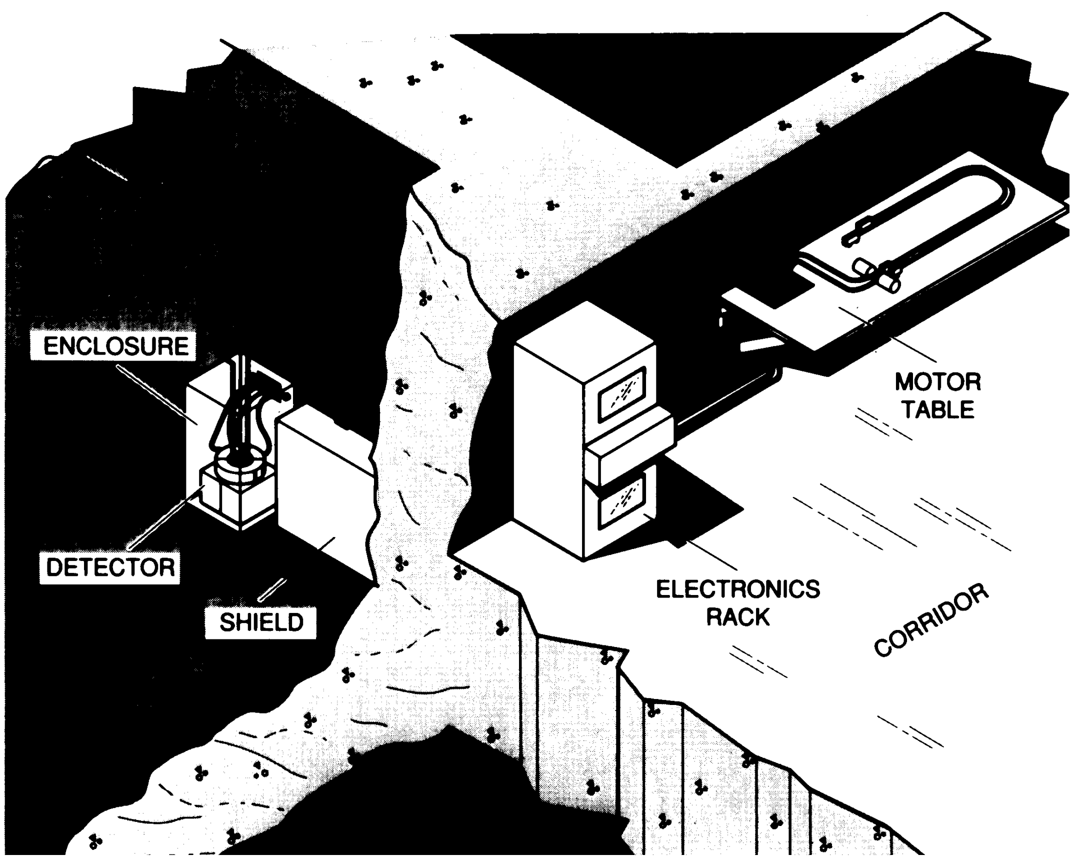


Fig. 17. A diagram of the components of the Liquid Raffinate Shuffler as they were installed inside and outside a hot cell. The detector head is inside the hot cell while the electromechanical components are readily accessible outside the hot cell. Phil Rinard led this project.

k. Dounreay Reprocessing Solid-Waste Shuffler

The breeder reactor fuel reprocessing plant at Dounreay, Scotland (UK), generates leached hulls and centrifuge bowls that may contain residual amounts of plutonium. Passive neutron counting is the usual way to measure plutonium masses, but it was impossible in this case because ^{244}Cm, a prolific neutron emitter, may be present. Fission products and attenuation ruled out gamma-ray methods. The British installed a D-T generator to induce fissions in plutonium, but it proved to be a maintenance problem for a continuously operating plant. Los Alamos installed a shuffler at Dounreay in 1987 and it has been an integral part of the plant's process ever since (Fig. 18).

The shuffler takes a passive count. If no neutrons are found, there can't be any plutonium. If the passive count is positive, it may be caused by plutonium, curium, or both. An active assay is performed for the plutonium mass (curium does not fission significantly). A 3-mg ^{252}Cf source, when new, is used to override the worst ^{244}Cm case. Baskets of hulls or bowl parts are scanned past the irradiation position and the various delayed neutron counts are added to indicate the total plutonium mass. The shuffler's computer controls the hoist to ensure that the basket's position is properly synchronized with the ^{252}Cf source.

The computer, the electronics, and the stepping motor mechanism were upgraded in 1995 to take advantage of recent advances.

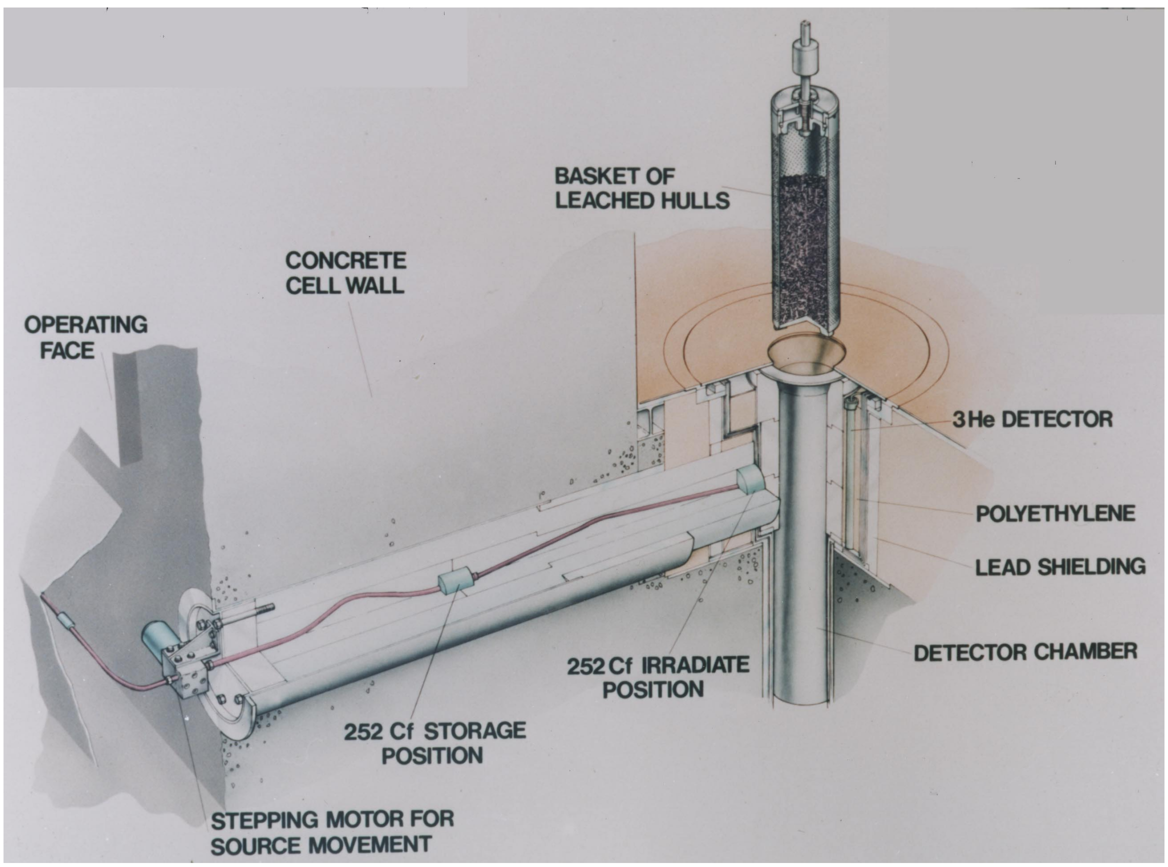


Fig. 18. The components of the Dounreay shuffler. A cylinder of polyethylene extends through the hot cell's wall and the ^{252}Cf source is stored in the center of the wall. A basket of waste is lowered into the assay chamber while measurements are taken. The electromechanical components are in the corridor on the left edge of this drawing. The original project was undertaken by Howard Menlove and George Eccleston; an upgrade was led by Phil Rinard.

4. Applications of Shufflers in Europe

The nature and applications of shufflers in Europe are similar to those in the US because we face similar problems.

Initially, ^{252}Cf sources were moved pneumatically in shufflers in the UK and France, as was suggested in the first Los Alamos paper on the shuffler concept. It is a rapid way to move the source and uses technology familiar to reactor workers. However, scanning a large object during irradiation cannot be done and variations in the time used to move the source are probably large (whereas constant times are preferred). Los Alamos shufflers have always used a stepping motor to move a strong, flexible steel cable to which the source is attached. This technique is fast, reliable, and accurate. The source also can be easily moved at a slow speed to scan a large object (such as a 55-gallon drum) during irradiation. The stepping motor and cable technique was adopted many years ago in both France and the UK. The French have even combined a more powerful motor with a large drum for winding the cable, resulting in even shorter times and longer distances to move the source.

Shufflers have been developed at Harwell in England for 208-liter (55-gallon) drums, bags of waste, and mixed fissile materials. Shufflers for liquid samples, dissolver tank residues, bags of waste, and 800-liter drums of leached hulls have been used at the Cadarache Nuclear Center in France.

C. Shuffler Basics

The ideal measurement condition has a strong signal in the presence of a weak background. Uranium's passive neutron signals are weak and the passive gamma-ray signals are easily attenuated to the point where they cannot reveal the uranium mass. The AWCC generates a strong signal by inducing fissions and counting the fission neutrons (with time correlation in the case of coincidence counting). However, the AmLi sources in the AWCC also produce a high background rate that limits the application of the AWCC to ^{235}U mass greater than 10 g. Increasing the AmLi source strength beyond 10^5 n/s is counterproductive because the background rate also increases and the precision of the net count rate is harmed rather than helped. Furthermore, the size of the object measured by an AWCC is limited to a diameter and height of about 10 inches; the nonuniformity of the irradiating neutron flux becomes prohibitive beyond these dimensions.

The shuffler can generate about the same signal or a stronger signal as the AWCC but with a much smaller background rate, even though it counts delayed neutrons that are less than 1% as numerous as prompt neutrons. The delayed neutron production rate is boosted by using a strong source (e.g., 10^{10} n/s) and the background rate is kept low by shielding the ^{252}Cf source during delayed neutron counting. The assay chamber can be relatively large (such as a 55-gallon drum) without sacrificing uniformity of irradiation because the small ^{252}Cf capsule can be easily scanned and the drum rotated during the irradiation.

For a detailed theoretical treatment of shufflers, see Ref. 1.

1. Delayed Neutrons

When a fission event occurs, two daughter nuclei are produced with a small number of "prompt" neutrons. The average number of neutrons released is usually between 2 and 3 (it is 3.76 for spontaneous fission of ^{252}Cf, which is exceptionally high). These daughter nuclei will sometimes emit additional neutrons seconds to minutes after the fission event; these are the "delayed" neutrons. These daughter nuclei are called "precursors" (of delayed neutrons). About 1.6% of the fission neutrons from ^{235}U are delayed, but only about 0.6% of ^{239}Pu's fission neutrons are delayed.

While it might appear that the signal with which a shuffler works is weak, it actually is strong because of the high intensity of the ^{252}Cf source. Count rates from Savannah River billets with 1.5 to 1.7 kg of ^{235}U are 1000 to 2000 counts/s, so after just a few minutes of counting the precisions of the counts are a small fraction of a percent. For 4.67 g-^{235}U in a 55-gallon drum containing iron scrap, a typical count rate is about 12 counts/s, so after a 1000-s measurement (including a 270s background count) the precision of the count is about 2%. The low background rate (typically 15 to 30 counts/s) helps makes these precisions possible.

The aggregate emission of delayed neutrons is accurately described by the sum of six simple exponential decays; each exponential is said to describe a "group" of precursors. The population *P(t)* or number of precursors present at time *t* is given by the following expression:

$$P(t) = \sum_{j=1}^{6} P_j(t) = \sum_{j=1}^{6} \beta_j \bar{\nu} e^{-\lambda_j t} \ . \qquad (1)$$

$P_j(t)$ is the population of the *jth* group of precursors. $\bar{\nu}$ is the average number of fission neutrons per fission (both prompt and delayed combined) and β_j is the fraction of the fission neutrons that are delayed, so $\beta_j \bar{\nu}$ is the average of delayed neutrons produced per fission by group *j*. The decay constant for group *j* is λ_j. These parameters of the six groups vary among the many uranium and plutonium isotopes (and others, such as thorium and neptunium) but are well known from measurements. These parameters are necessary to calculate required ^{252}Cf masses or expected count rates.

To gain a sense of the values of these parameters, examine Table I for the parameters of ^{235}U and ^{239}Pu. The groups' half-lives are shown instead of the decay constants for quicker understanding of the behavior of delayed neutrons. (Uncertainties are omitted, but can be found in Ref. 1.) If one assay is to follow another, as in a precision check, there should first be a pause to allow the previously produced precursors to decay; 4 minutes is generally sufficient because the longest-lived precursors are not the most productive. The time decays of the precursors of these two important isotopes are shown in Fig. 19; the amplitudes are per fission and reflect the different values of $\beta_j \bar{\nu}$. The two values of $\bar{\nu}$ in Table I are somewhat approximate because $\bar{\nu}$ actually has a slight dependence on the energy of the captured neutron.

TABLE I
DELAYED NEUTRON PARAMETERS FOR ^{235}U AND ^{239}Pu

	^{235}U. $\bar{\nu}$ = 2.43*		^{239}Pu. $\bar{\nu}$ = 2.88*	
Group j	$T_{1/2}$ (s)	$\beta_j \bar{\nu}$	$T_{1/2}$ (s)	$\beta_j \bar{\nu}$
1	55.72	0.00052	54.28	0.00021
2	22.72	0.00346	23.04	0.00182
3	6.22	0.00310	5.60	0.00129
4	2.30	0.00624	2.13	0.00199
5	0.610	0.00182	0.618	0.00052
6	0.230	0.00066	0.257	0.00027
sum	-------	0.01580	-------	0.00610

* These values are for thermal neutron fission. Actual values generally are slightly larger.

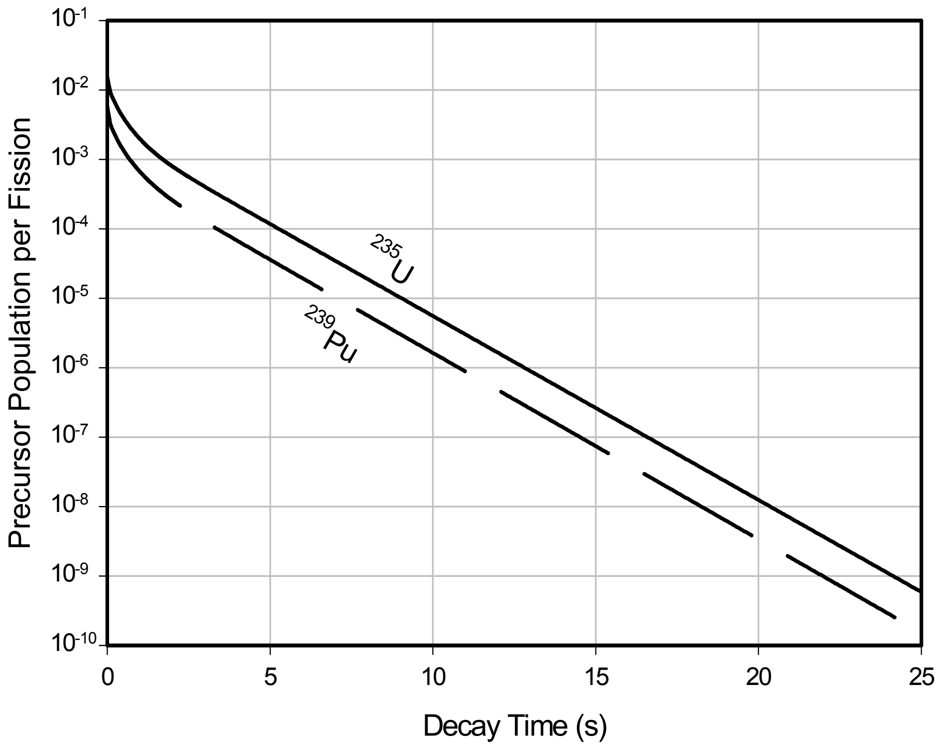


Fig. 19. After a fission, the average number of delayed neutron precursors present is shown as a function of time after the fission. The curve for an isotope is accurately expressed as a sum of six curves (one for each precursor group). Each group has an exponential decay but their sum isn't exponential until the short-lived precursors have decayed for about 5 s.

2. The Shuffler Principle

The principle behind a shuffler assay is illustrated in Fig. 1. The general shape of the standard 55-gallon-drum shuffler is used in this illustration. If an assay is to be done in a specified time, optimum times of the various stages can be calculated to optimize the precision of the resulting count rate. For example, in the standard 55-gallon-drum shuffler, the typical assay time is somewhat arbitrarily set at 1000 s. The background count uses the first 270 s of this time and the background rate is about 20 to 30 counts/s. Generally, 34 shuffles are performed, during each of which the irradiation is about 11.6 s long and the count time is about 7 s. The rest of the 1000 s (about 98 s) is spent moving the source and handling the intermediate data. The precision changes slowly as these times are modified, so the times are not critical to getting good precision. It is important that the times of all the steps are closely replicated during each of the shuffles; this is easily done by the computer and stepping motor combination to within a millisecond or so.

The software allows the user to easily modify any of these parameters to best match the current circumstances. If the assay time is doubled to 2000 s, the background time should also be doubled (to 540 s) and the number of shuffles doubled (to 68). The irradiation and count times for a given shuffle should not be changed because they are based on the nuclear parameters in Table I and the background rate. Should the background rate be much higher than 30 counts/s, the irradiation and count times should be reconsidered, as described in Ref. 1.

During a 7-s count most, but not all, of the delayed neutrons will be released (Fig. 19). A small number will "carry over" into the next count time. Better use of the assay time is made by "sacrificing" some of the delayed neutrons and re-irradiating to replenish the precursor population. See Ref. 1 for more details.

3. Pertinent Properties of ^{252}Cf

a. Nuclear Properties

The most important property of ^{252}Cf for shuffler applications is its very high yield of neutrons from spontaneous fissions: 2.34 x 10^{12} n/s•g. This is 10^5 times greater than the yield from ^{244}Cm and 2 x 10^9 times greater than the yield of ^{240}Pu. It has the intensity of a small accelerator without the electronics and irregular variations in yield, plus a lower neutron energy. However, it cannot be turned off and it disappears with a half-life of 2.645 yr whether it is used or not.

For those who deal in curies, one gram of ^{252}Cf corresponds to 536.1 Ci. So 1 mCi of ^{252}Cf corresponds to a yield of 4.635 x 10^6 n/s, and 1 μCi gives 4635 n/s.

The half-life is short enough so that a source must be oversized initially to have a specified useful lifespan in a shuffler. For a source to have a useful lifespan of at least three years, it must be at least twice as large as necessary. Practical lifetimes are closer to 10 years, either because initial sizes are four times the minimum required, the precision is preserved by increasing the assay time, only materials with masses larger than the design minimum are measured, or some degradation of precision is acceptable.

Shufflers use only the fact that ^{252}Cf emits neutrons, not the fact that these are fission neutrons with time correlations from spontaneous fissions. The energy spectrum of these spontaneous fission neutrons is very important in shuffler applications. The most common expression for the energy distribution is the following Watt expression for the relative number of neutrons with energy E:

$$N(E) = e^{-E/a} \sinh(\sqrt{bE}), \tag{2}$$

where E is the neutron energy in MeV and, for ^{252}Cf, a = 1.025 MeV and b = 2.926 MeV^{-1}. The average neutron energy is 2.3 MeV but the most probable energy is 0.90 keV. The median energy is 3.27 MeV. The spectrum and these statistics are shown in Fig. 20. This spectrum is used in the Monte Carlo code MCNP calculations discussed later, as recommended by the MCNP manual.

^{252}Cf is produced in the high-flux reactor at Oak Ridge. The chemical separation cannot distinguish among the various californium isotopes, so each batch has an isotopic mixture that depends on the target material and reactor irradiation. So when we say we are using a ^{252}Cf source, that is a simplification. But the neutron emission rate from the ^{252}Cf normally dominates those from other isotopes and the yield of the source decays with the half-life of ^{252}Cf.

However, with the passage of time the longer-lived ^{250}Cf (13.2 years compared to ^{252}Cf's 2.645 years) can produce a noticeable fraction of the neutron emission rate. The specific emission rate from ^{250}Cf is only about 1% that of ^{252}Cf and less of it is produced in the reactor, but it decays much more slowly. After a decade the emission rate from ^{250}Cf could be 1% that of ^{252}Cf; after two decades, it could be 4%; after three decades, it could be 25%.

So when a Cf source is used for an absolute measurement (such as detector efficiency), the additional neutrons from ^{250}Cf should not be ignored if the source is more than 10 years old. But the correction for ^{250}Cf cannot be made without knowing how much there is relative to ^{252}Cf, and this ratio varies widely among production batches. It is important to obtain a report giving the relative abundances of the Cf nuclides when a source is purchased.

Table II presents the basic nuclear data used by the Radiochemical Engineering Development Center and Oak Ridge, where Cf is generated and sources are produced. John Bigelow and Joe Knauer kindly provided this information.

For four of these six nuclides ($^{250, 251, 252, 254}Cf$) it is easy to calculate the emission rates given in Table II. The expression is:

$$\text{Emission rate} = \bar{\nu}\ \text{(SF Branching Fraction)}\ [(\ln 2)/T_{1/2}]\ [6.02214 \times 10^{23} / \text{at. wt})]. \tag{3}$$

To get the emission rate in (n/g•s), the half-life must be in seconds. The spontaneous fission branching fraction is normally 1 minus the α-decay branching fraction. "At. wt" is the atomic weight of the isotope.

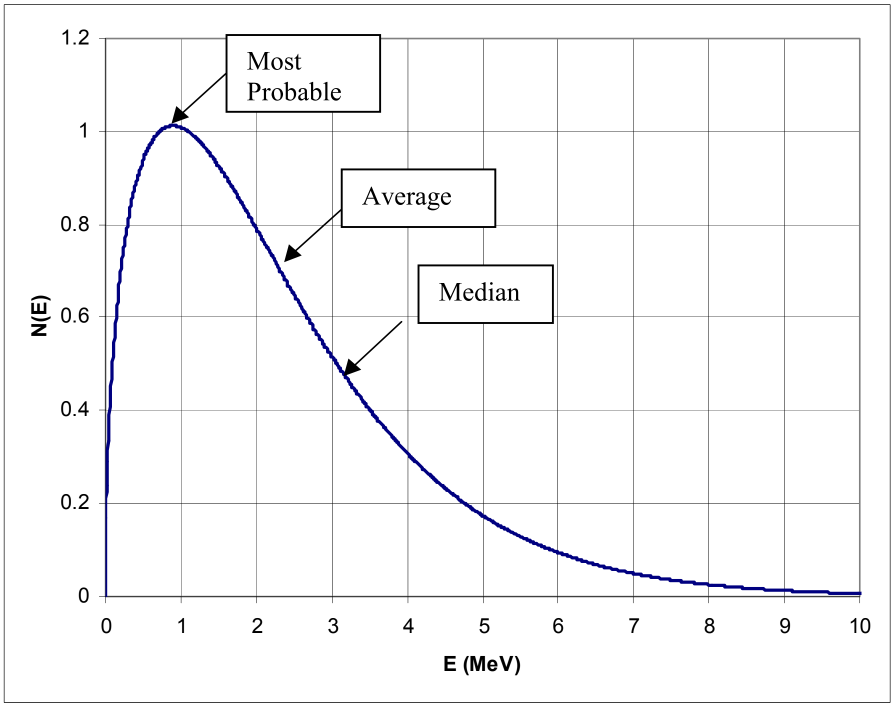


Fig. 20. The energy spectrum of ^{252}Cf neutrons from spontaneous fissions. The average energy, the most probable energy, and the median energy are marked.

TABLE II
BASIC NUCLEAR DATA FOR Cf NUCLIDES

Nuclide	Half-Life ($T_{1/2}$)	α-Decay Branching Fraction	Spontaneous Fission (SF) Branching Fraction	$\bar{\nu}$ for SF	(α,n) Rate from Oxygen per Gram of ^{x}Cf	Total Neutron Emission Rate (n/g•s)
^{249}Cf	351 y	≈ 1.0	5.2 x 10^{-9}	3.4	≈ 3700	6.34 x 10^{3}
^{250}Cf	13.20 y	0.99921	0.00079	3.53	negligible	1.117 x 10^{10}
^{251}Cf	898 y	≈ 1.0	9.0 x 10^{-6}	3.7	negligible	1.955 x 10^{6}
^{252}Cf	2.645 y	0.96904	0.03096	3.768	negligible	2.314 x 10^{12}
^{253}Cf	17.81 d	0.0031	unknown	unknown	negligible	8.406 x 10^{4}
^{254}Cf	61.9 d	0.00299	0.99701	3.93	negligible	1.204 x 10^{15}

The neutron emission rate is not readily calculated for ^{249}Cf because of the (α,n) reactions. For the other isotopes this source of neutrons is negligible, but for ^{249}Cf the (α,n) production rate is larger than the production rate from spontaneous fissions. The actual rate is poorly known (probably to one figure only), so the precision of three figures in the total rate given in Table II is optimistic.

Another difficult case is ^{253}Cf. In this case the dominant decay mode is beta, not alpha or spontaneous fission. The branching fraction for spontaneous fission is not known and cannot be calculated from the branching fraction for alpha decay. The total neutron emission rate in Table II is simply the value used at Oak Ridge.

Fortunately, the worst uncertainties have no practical significance for shufflers because only two nuclides have important emission rates in a source: ^{250}Cf and ^{252}Cf. The half-life of ^{254}Cf is too short to survive by the time a source is received, so its huge specific emission rate has no impact. The production protocol is optimized for ^{252}Cf with its modest half-life, so the long-lived nuclides are not as abundant and the short-lived nuclides are gone before the source reaches a user regardless of the nuclides' initial relative amounts.

Figure 21 shows the relative neutron emission rates from ^{250}Cf and ^{252}Cf (plus their sum) for three decades after creation. The initial relative abundances used are shown in Table III. The ^{250}Cf fraction of the neutron emission rate is shown in Fig. 22.

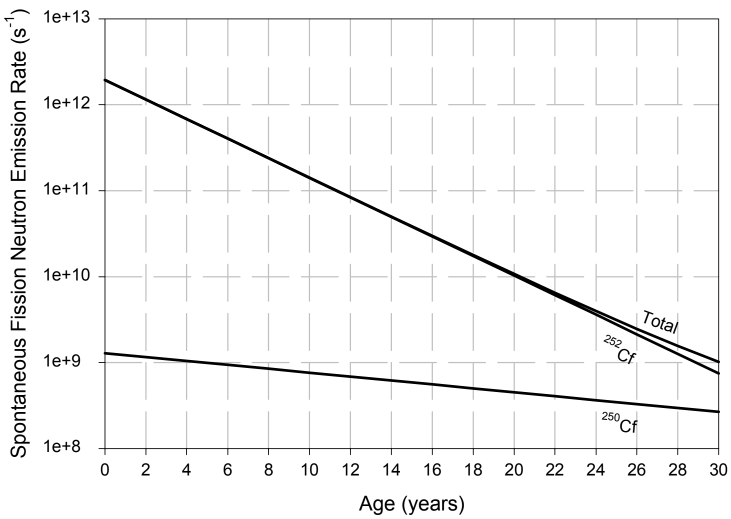


Fig. 21. These are the important neutron emission rates as a function of time from one gram of Cf with the mixture of nuclides given in Table III. The lowest curve is the rate from ^{250}Cf; the middle curve is the rate from ^{252}Cf; the upper curve is the sum of these two rates. Emission rates from other Cf nuclides are negligible. The curves for ^{252}Cf and the sum are indistinguishable on this scale until an age of about 20 years.

TABLE III
INITIAL RELATIVE ABUNDANCES OF Cf NUCLIDES
This is a realistic example, but abundances vary among batches.

Nuclide	Relative Abundance (Fractional)
^{249}Cf	0.009424
^{250}Cf	0.115183
^{251}Cf	0.032461
^{252}Cf	0.837696
^{253}Cf	0.005236
^{254}Cf	0.000000

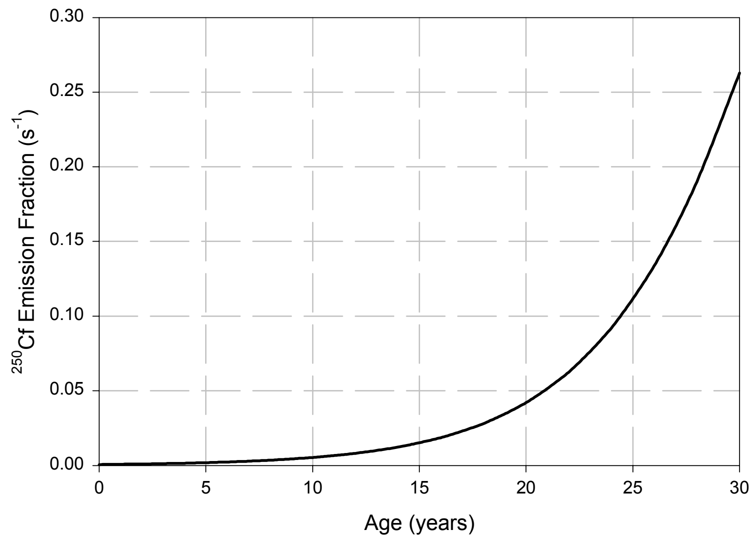


Fig. 22. The ^{250}Cf fractional contribution to the total neutron emission rate from the Cf described in Table III increases with time because the ^{252}Cf decays more quickly. It takes 13 years for ^{250}Cf to contribute 1%, but only an additional eight years (21 years total) to reach 5%. The fraction grows to 25% in another nine years (30 years total).

In practice, it has been possible to ignore californium isotopes other than ^{252}Cf in shuffler applications because a source is not used for 20 years. But an old shuffler source has other uses and its current mixture of isotopes should be understood to avoid inaccurate results.

The neutron dose rate from 1 µg of ^{252}Cf at one meter without any shielding is 2.34 mrem/hr. The gamma rays contribute another 0.140 mrem/hr under the same conditions. The total dose rate is therefore 2.48 mrem/hr/µg at one meter with no shielding. The standard 55-gallon-drum shuffler uses a 550-µg source when new, so the dose rate at one meter in air for such a source is 1.24 rem/hr. When loading a new source into a shuffler, the source is unshielded for perhaps 15 s and nobody is closer than about 2 meters. Under those conditions, the nearest person receives about 1.4 mrem. Doses measured by dosimetry during the loading process have been about 10 mrem, which includes the dose received from working around the shipping cask to prepare for the brief loading operation. The short time needed to insert a new source is the key to producing such a small dose to the handler and practice with a dummy source helps keep the time short.

b. Source Packaging

The main advantage of using of ^{252}Cf for shuffler applications is the tiny mass and volume needed for a source with a large yield (e.g., 10^{10} n/s). All of the standard capsules overwhelm the size of the actual source; the capsules are made almost entirely of solid steel. The californium may be electrodeposited on a small wire, which is cut in pieces to produce various neutron yields.

Los Alamos shufflers have used standard, certified packages used for decades by Oak Ridge and Savannah River. The californium is double encapsulated in steel. The inner capsule (Model 10) has a small cavity for the wire (or other carrier of the californium, a diameter of about one-fifth of an inch, and a length of about 1 inch. This capsule goes inside an outer capsule (Model 100), which has a diameter of about one-third of an inch and a length of about 1.5 inches. Both capsules are welded shut and have passed extensive durability tests under conditions much worse than a shuffler can give.

One end of the outer capsule has a threaded nub. A steel coupler designed at Los Alamos screws onto this nub and also onto a flexible steel cable with a wire wound around the outside, which serves as a coarse thread. All threads and set screws are cemented with LokTite to ensure that they will not come undone. (Heat softens the cement, so the attachments can be undone when necessary.) The many sources attached in this manner have never accidentally detached from the cable, despite the immense number of shuffles of the sources.[8]

The cable is from Teleflex, which also sells gears and taps to make threads that match the cable forming the coarse thread. These cables were developed for airplane and boat guidance mechanisms (rudders, elevators); their strengths are not challenged by the demands of a shuffler. The gear that drives the cable (and therefore the source) is in turn driven by a stepping motor controlled by a computer.

4. Factors That Complicate Assays

While it is easy to place an object in a shuffler and record the delayed neutron count rate a few minutes later, converting the count rate to an accurate mass of ^{235}U (or some other fissile isotope) requires careful preparation. In other words, calibration is important, but not always simple. A balance or scale doesn't care if a kilogram of lead or a kilogram of feathers is placed on it; the weight is still one kilogram. Most neutron- and gamma-ray-based NDA instruments are not so indiscriminate because the form of the fissile material and even the nonfissile matrix will usually affect the detectors' responses. The shuffler shares these complications, so it also has features to mitigate them.

When the goal is to measure the mass of ^{235}U, there is always some amount of ^{238}U present. The probability of ^{238}U fissioning is essentially zero unless the energy of the absorbed neutron is more than 1 MeV. But the ^{252}Cf energy spectrum of Fig. 19 makes it clear that, unless modified, there will be fissions in ^{238}U. Actually, some fissions in ^{238}U occur regardless of the energy spectrum of the irradiating source (including AmLi) because fission neutrons from ^{235}U have an energy spectrum not too different than those from ^{252}Cf's; of course, the intensity of ^{235}U's neutrons is much less than those from ^{252}Cf. Some relief for this problem comes from the lower probability that a neutron with high energy will induce a fission in ^{238}U, but this is less than a factor of two. With highly enriched uranium there is more relief from the smaller quantity of ^{238}U (10% or less). On the other hand, the average number of delayed neutrons from a fission of ^{238}U is 2.6 times that of ^{235}U. The whole ^{238}U complication can be nearly eliminated with "spectrum tailoring," that is by reducing the energies of the ^{252}Cf neutrons below 1 MeV before they reach the uranium. This has been done in two shufflers (the Bathtub and Scrap shufflers) by surrounding the ^{252}Cf by one or more metals and letting the scattering of the neutrons reduce their energies. The other option is to accept the contribution of delayed neutrons from ^{238}U and make them part of the calibration. The best solution depends on the circumstances. In the Scrap Shuffler, there was space for the extra metal and the increase in ^{252}Cf mass was tolerable. In the Billet Shuffler, there was no ready space for the extra metal, and to make space would have led to a much larger ^{252}Cf mass, requiring much more shielding to meet the newer, more-stringent shielding requirements.

While fissions in ^{238}U require high-energy neutrons, fissions in ^{235}U are more likely as the neutron energy decreases. Neutrons directly from ^{252}Cf have one probability of inducing fissions in ^{235}U, but neutrons that have scattered off the walls of the assay chamber, matrix materials, or even the uranium itself are more likely to induce fissions if they encounter the ^{235}U because they have lower energies. An extreme example is the Liquid Raffinate Shuffler, where the matrix was an organic solvent. This excellent moderator with the uranium uniformly dispersed throughout caused a thermal neutron irradiation despite the initial neutron energy spectrum of Fig. 19; the initial energy spectrum was immaterial because most neutrons were thermalized quickly and had an extremely high probability of inducing fissions in ^{235}U. At the other extreme, the Billet Shuffler was designed to keep the neutron energies as high as possible to give as uniform a penetration of the metal as possible; the ^{238}U complication was dealt with through calibration. The various matrices that might be put into the standard 55-gallon-drum shuffler have a wide range of effects[3] that have been examined and dealt with in various ways. Within such a large volume as a 55-gallon drum, the same mass of ^{235}U can produce different count rates depending on its distribution throughout a moderating matrix, so a method of determining the distribution and correcting for it has been developed and implemented.[7]

Many of the Los Alamos shufflers were built for a specific purpose and could serve another only with difficulty. The standard 55-gallon-drum shuffler is an exception and has a great deal of flexibility. Its large assay chamber can hold most uranium-bearing containers, including some fuel pins, so it has assayed most items imaginable in a uranium inventory. Just obtaining a count rate verifies the presence of fissile material, but usually measuring a mass of ^{235}U is the goal. Calibration standards for miscellaneous items do not exist and never will—many are one of a kind and making standards for them is clearly impractical. Fortunately, it is possible to calculate calibrations that are as accurate as the knowledge about the items to be measured.[2] If the material is a powder, how well is its density known? This has a second-order effect on both the measured and calculated count rates. If the item is uranium metal, is its shape known? A sphere and a rod of the same mass will give quite different count rates because of differences in self-shielding (Appendix A) and multiplication (Appendix B). But with the best available information, calibrations can be calculated. This has been done successfully for AWCCs as well as shufflers; the process has to be done carefully and should be benchmarked as much as possible. The standard 55-gallon-drum shufflers at Los Alamos have some excellent U_3O_8 and uranium metal standards, so these were used to benchmark the calculational process.

II. Shuffler Performance

The performance of any NDA instrument is expressed by a set of pertinent quantitative parameters. The most commonly used parameters are defined here. They are also common to other instruments.

- Precision or Reproducibility. These two words are used as synonyms here, but only "precision" will be used. If a measurement is repeated many times, the precision is the standard deviation of the results. It may be expressed in the same units as the measurement, or as percent of the average of the measurements. In the latter case, it is called a relative precision. The standard deviation is often expressed in units of the σ of normal (or Gaussian) distributions, where $\pm 1\sigma$ gives the range of values in which 68.3% of the measured values should fall (ideally). The $\pm 2\sigma$ range should encompass 95.4% of the measurements and $\pm 3\sigma$ should contain 99.7% of the measurements. The item measured may be left untouched during this process or removed and replaced between measurements to include handling effects in the precision. The time span of the measurements may be short (less than a day) or long (many days or years) to exhibit stability over the time span.
- Accuracy. This is a comparison of the measurement result and the best estimate of the true value. The difference in the two values is usually expressed as a percent of the true value; a smaller percent means better accuracy. Sometimes "bias" is used in this same sense, but because it is used in so many different ways, it will not be used here. Sources of inaccuracy are sorted into systematic and random causes. The most notorious random causes are inherently beyond full control. Examples are the randomness in radioactive decay and backgrounds from cosmic rays. Cosmic-ray problems can be mitigated with shielding and other techniques, but because it is impractical to do all work in deep mines, the cosmic-ray problem is almost always present in one degree or another. Systematic inaccuracies are caused by incomplete knowledge of the instrument, its calibration standards, or the materials being measured. Whatever errors exist in the characterization of the calibration standards are passed along to the assay results. If the detection efficiency is an important parameter in the data analysis, the error in its "known" value is also passed through into the measurement results as another systematic error.
- Sensitivity or Minimum Detectable Mass. These two terms are taken as synonyms here, but whichever is used requires some supplementary information before it has any meaning. The usual way to express sensitivity, or the smallest mass that can be said to be measured with a stated certainty, is to relate the signal and noise "strengths" and define when the signal is just distinguishable from fluctuations in the noise. In shufflers, the signal is the count rate of delayed neutrons (perhaps expressed as a corresponding fissile mass), while the noise is from background neutrons. A common practice is to define the sensitivity as the mass of fissile material that generates a delayed neutron count rate that is 3 times larger than its 1σ precision value. The ratio is sometimes taken to be 2 or 4 instead of 3. The 1σ value includes all the known random and systematic sources of inaccuracy.
- Assay Time and Throughput. These are related, but not identical, concepts. The assay time here is the time it takes to perform a background count and then complete the preset number of shuffles to irradiate the material and count delayed neutrons. Throughput is how many measurements can be completed in a given time. Throughput uses the assay time, but includes the time needed to change items to be measured and to enter information into the shuffler's computer. The assay time may be 1000 s (16.67 min.) but the throughput might be three items an hour. Assay time directly affects precision and sensitivity, and it affects accuracy through precision.

With this terminology defined, each performance characteristic will be examined for shufflers. Actual performances will be used as examples and ways to improve performance will be given.

A. Precision

Precision is a strength of shufflers. An intense ^{252}Cf source can be used to generate a large count rate of delayed neutrons and yet the background rate is low because the source is shielded while the delayed neutrons are counted. The precision also depends on the mass of fissile material present and the specific fissile isotope involved. The probabilities of fissioning ^{235}U or ^{239}Pu are quite similar over a wide range of neutron energies, but ^{235}U produces about 2.6 times as many delayed neutrons per fission while spontaneous Pu fissions raise the background rate, affecting the precision. Everything else being equal, the precision with ^{235}U is better than with ^{239}Pu. This is also true when ^{235}U is compared with ^{233}U, ^{238}U, and ^{237}Np, just to name a few more isotopes.

But conditions are not always equal, and the precision of a count with ^{239}Pu may be better than with ^{235}U for one or more reasons. There may be very little ^{235}U; there may be more moderator mixed with the ^{239}Pu; the count time for ^{239}Pu is longer; the ^{252}Cf source is weaker for the ^{235}U case; the ^{239}Pu has a geometry that gives a large multiplication; or the background rate for the ^{239}Pu is much lower than for ^{235}U (an unusual circumstance that might be caused by (α,n) reactions, for example).

The hardware of the shuffler affects the precision. Most of the hardware is fixed. However, the assay chamber is usually lined with cadmium to keep very low energy neutrons out of the assay chamber; this liner may be removed in just a few minutes. With everything else held the same, the precision can be greatly improved by not using a cadmium liner. The low-energy neutrons emerging from scatters within the moderating walls will have high probabilities of inducing fissions and the count rate is greatly boosted. This can be an effective technique in some circumstances, but it is generally a poor assay technique. The goal of an assay is not to get the best possible precision, but to get the best possible accuracy. If low-energy neutrons are allowed to dominate the fission events, the correlation between count rate and fissile mass will become more complex as the mass grows. The self-shielding effect (Appendix A) is accentuated by low-energy neutrons and accuracy suffers.

Precision is important but it is only a contributor to accuracy. If the mass of fissile material is small or well dispersed into small particles, it may be possible to remove the cadmium and improve both precision and accuracy. But this should not be done without a thorough understanding of the circumstances and consequences. An alternative will be described later where reduced-energy neutrons have a positive effect, but it was brought about not by removing the cadmium liner, but by essentially changing the matrix around the fissile material. Both precision and accuracy were greatly improved, but the caution flag should be out until it is proven that the consequences of such a technique are understood.

Table IV lists ways to improve precision, with cautionary notes.

A comparison was made of two methods for analyzing shuffler data: the Los Alamos method of summing delayed neutrons for several seconds and the Cadarache, France, dieaway method of counting neutrons during many successive short time intervals ($\approx$0.078 s).[9] The Los Alamos method essentially uses the area under the die-away curve to determine the average count rate; the Cadarache method uses the amplitude extrapolated from a curve fitted to the die-away data. The average count rate method gives a better precision for the same data (9% vs. 19% for a ^{239}Pu solution; 0.30% vs. 0.48% for ^{235}U in sludge). However, the accuracies of the two methods were essentially the same because precision was not the most important contributor, as will be seen in the next section.

TABLE IV
Improving Precision

To improve precision…	But be aware that…
Use a larger ^{252}Cf source.	More shielding will be required and the size and weight of the shuffler will grow exponentially.
Shorten the irradiation distance between the ^{252}Cf source and the fissile material.	If this produces a large inequality in the neutron flux among different locations where fissile material may exit, the assay's accuracy can suffer as the distribution of fissile material changes among items.
Use a metallic reflector behind the ^{252}Cf source to send more neutrons toward the fissile material.	This will never hurt the precision, but there may not be space for the 2 to 4 inches of iron (or another dense metal).

To improve precision…	But be aware that…
Surround the ^{252}Cf with metal to "tailor" the neutron energy spectrum toward lower energies.	Unwanted fissions in fertile isotopes (like ^{238}U) may be reduced, but self-shielding effects will be greater and the source will have to be somewhat stronger.
Use thermal and epithermal neutrons.	Self-shielding will be a much larger problem even though count rates may increase.
Measure larger fissile masses.	The choice of masses to measure is usually beyond the user's control. Self-shielding and multiplication effects will grow, sometimes balancing each other nicely, but usually not.
Use longer assay times.	Throughput will decrease.
Use low background rates.	Poorly designed shielding may increase cosmic-ray interactions and hence the background rate. A larger storage block for the ^{252}Cf source will reduce the background rate, but is the reduction commensurate with the increase in cost and improvement in performance?
Use more detector tubes or tubes with better sensitivity.	The procurement and fabrications costs will increase.

B. Accuracy

Accuracy requires precision, but precision does not ensure accuracy. If the delayed neutron count rate is poorly known, the best calibration curve in the world cannot produce an accurate result. But a count rate with fantastic precision is meaningless without an accurate calibration curve.

Accuracy is a relative term and depends on the use to be made of the result. A verification measurement checks a declared value, but is not expected to be as good as the declared value and will not replace it; this is not a demand for great accuracy. Accountability measurements are to give the best possible values and may replace the declared values of inventory items; they require the best possible accuracy. For waste quantities, a poor accuracy may be tolerable because a large error in a small mass is another small mass; a 100% error in 1 g is only 1 g itself. But improving the accuracy becomes important when the measured mass plus some multiple of its uncertainty bumps into a regulatory mass limit. In this case, the waste may have to be placed in a more stringent category where handling and storage is more expensive.

The following shufflers made for Savannah River were specified to have exceptional accuracies that could be met because kilograms of uranium were involved: the Scrap Shuffler (0.3% for chips; 1.5% for floor sweepings), the Product Oxide shufflers (0.36%), and the Billet Shuffler (0.5%). On the other hand, the Liquid Raffinate Shuffler was specified by the Westinghouse Idaho Nuclear Co. to have the relatively poor accuracy of 10% because it was more important to complete an assay in only 100 s with a concentration of only 0.034 g/L (or 0.07 g-^{235}U in the 2-liter assay chamber).

Because a shuffler's precision is usually very good, the accuracy is primarily set by the quality of the calibration. For the excellent accuracies of the three types of Savannah River shufflers mentioned above, the calibrations were extensive. Standards were carefully prepared and sampled for chemical analysis. In the case of the Billet Shuffler, the billets had been fabricated to small tolerances, so variations among billets of the same model were small except for the ^{235}U enrichment. The metal pieces for the Scrap Shuffler had irregular geometries, but this was not a major point. The Product Oxide shufflers had to work with oxides whose densities could vary, but with careful handling the variation was slight.

Standards based on powders (e.g., U_3O_8) require special attention because a powder's density will change with handling or even while sitting on a shelf. The density of a powder can be changed perhaps by as much as 20% by shaking or tapping a can.[10] This changes the self-shielding of the material and, therefore, the count rate. A handling procedure should be established and adhered to strictly to make sure the calibration curve is appropriate for each measurement.

Figure 23 shows qualitatively how variations in a material can affect the accuracy of the calibration curve. The effects are somewhat exaggerated for clarity. Figures 24 and 25 present quantitative examples of measured and calculated effects of changes in chemical and physical form.

At the end of the previous section, the Los Alamos and Cadarache methods for counting and analyzing the delayed neutrons were described. Despite a small advantage in precision of the average count-rate method over the die-away amplitude method, the two accuracies were comparable because the uncertainties in the calibration parameters were larger than the precisions. Expensive measures to improve precision are not cost-effective if the accuracy is dominated by the quality of the calibration.

The electromechanical system that drives the ^{252}Cf source in a shuffler must perform its operations in a very reproducible manner. Otherwise the reproducibility (i.e., precision) and accuracy will suffer. The stepping-motor systems have fulfilled this need and corrections for irregularities are not needed (although they are calculated as a check on the health of the electromechanical system).

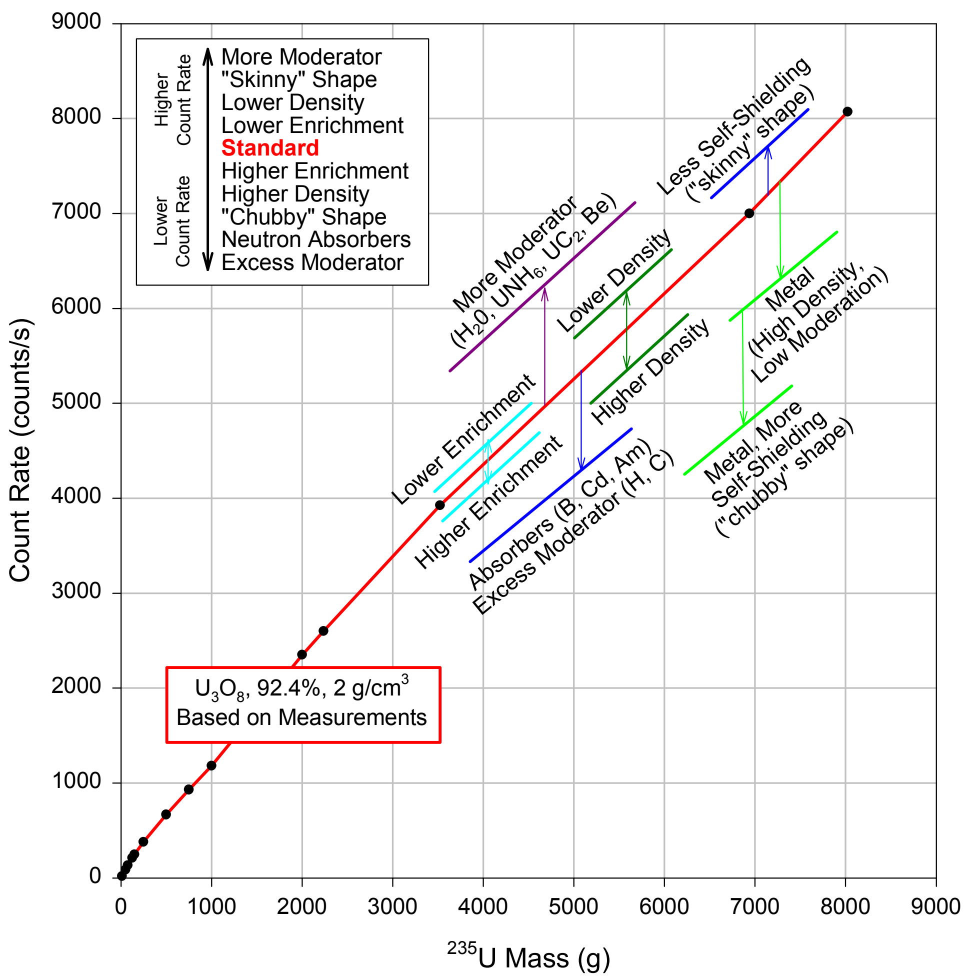


Fig. 23. When the material being measured has some characteristics different from the calibration standards, the accuracy can be adversely affected. In this example, the calibration shown by the red line was for dry U_3O_8 with 92.4% and a density of 2 g/cm^3. A list of potential changes to the material is shown and the qualitative effect of each is indicated (somewhat exaggerated for clarity).

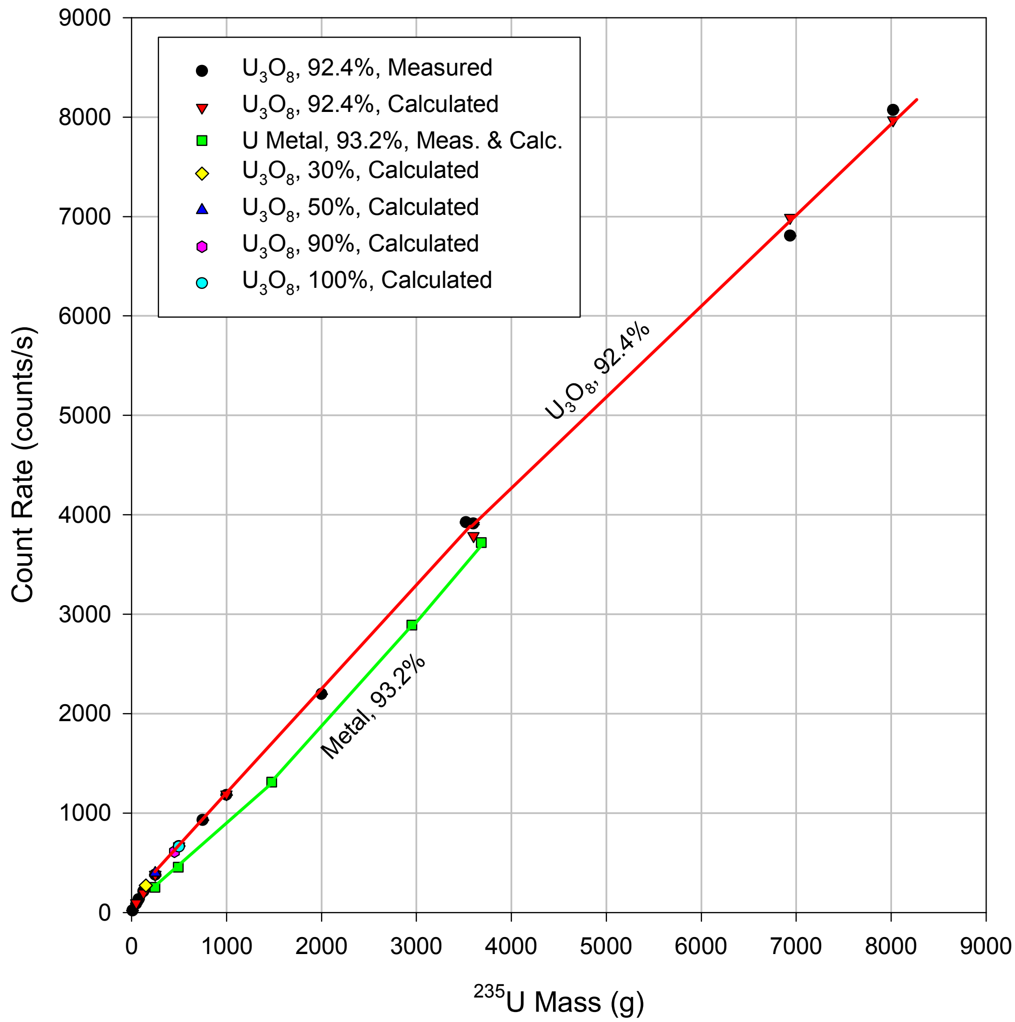


Fig. 24. The curve in red is the measured calibration curve for dry U_3O_8, 92.4% enriched. The effect of deviations from this has been calculated and is shown for comparison. Using metal disks (6 cm diameter) greatly reduces the count rate for the same mass of ^{235}U because of self-shielding from the higher density (19 instead of 2 g/cm^3). Enrichment effects are better seen in Fig. 25, which is an enlargement of the low-mass portion of this figure.

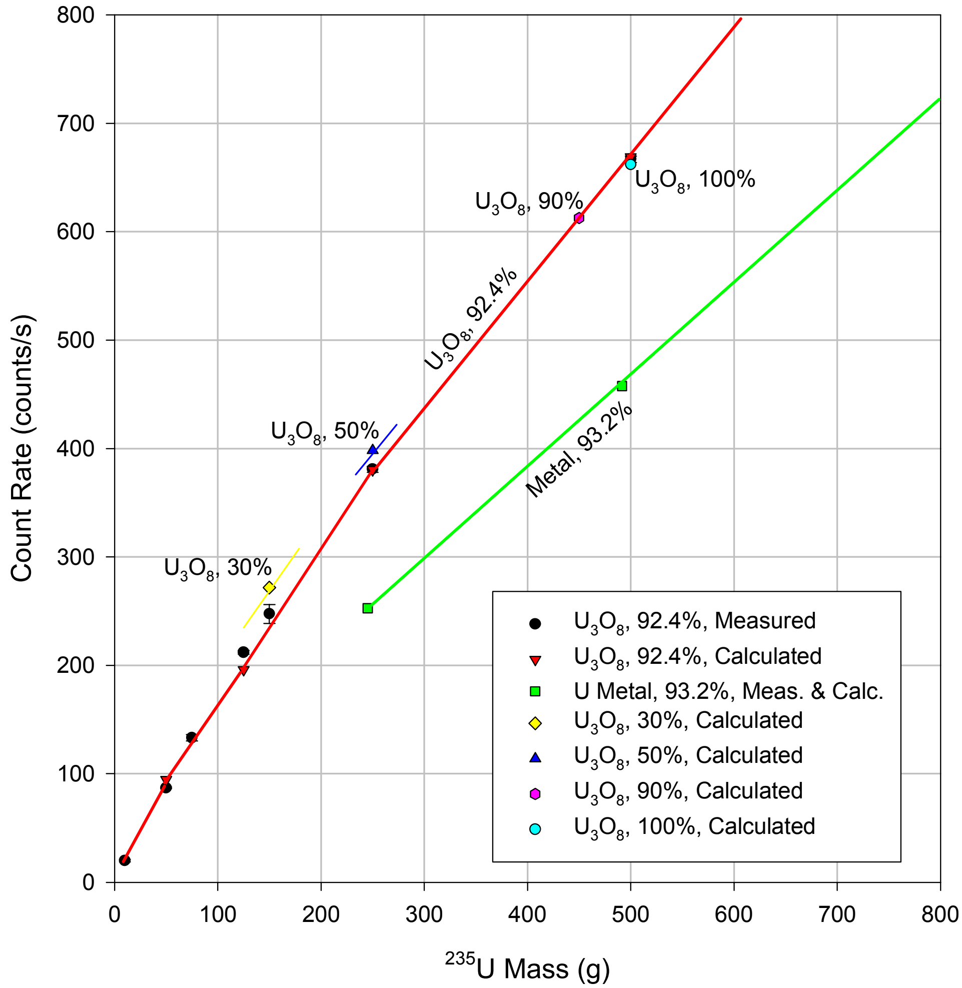


Fig. 25. The low-mass portion of Fig. 24 is shown in more detail. Some calculations were done for dry U_3O_8 that reproduced the calibration curve with 92.4% enrichment and then examined the effect of different enrichments. 500 g of U_3O_8 was studied for 30, 50, 90, and 100% enrichments. The lower the enrichment, the more ^{238}U is present to add delayed neutron counts to those from the ^{235}U. The abscissa only uses the ^{235}U mass, so the counts from ^{238}U place the data points above the calibration curve. At 90% enrichment, the difference with the curve is negligible. At 100% enrichment, the data point is slightly below the curve.

There are several ways to extend a calibration to minimize the number of standards required. For example, a 55-gallon drum of waste paper has a large amount of hydrogen that has a large effect on the count rate. A calibration done with one amount of paper will have an accuracy problem for another drum with a paper density that differs by, say, 20%. You could have another calibration curve to handle this second drum, but how would you know which calibration to use on a drum? You could weigh a drum, but what assurance is there that something else besides paper hasn't changed the weight (such as a piece of metal)? The difficulties of using more than one paper-filled calibration drum are avoided by the flux monitors built into the shuffler. These are low-efficiency ^{3}He tubes that count during the irradiation periods. Although some of the counts are of neutrons that come directly from the ^{252}Cf source (similar to the background counts in an AWCC), many others are from neutrons that entered the drum, underwent collisions, and emerged with reduced energies. By using two flux monitors, one wrapped in cadmium and one not, the ratio of their counts is independent of the ^{252}Cf source strength (avoiding the nuisance of having to adjust the flux monitors' parameters when a new source is installed). The cadmium-wrapped tube is much less affected by moderators in a drum than is the bare tube, so the ratio can be correlated with moderator density. By using a small number of drums with different paper densities, the flux monitors can be primed to correct for these variations in subsequent drums. The range of application of this correction may be made rather large, but it is always best to use the smallest range necessary.[3] However, this flux-monitor correction assumes that the fissile material is always distributed the same way throughout the container and blindly applies the same correction factor, regardless. This is acceptable when distributions truly are the same, but introduces an error when they are not.

One way to reduce such an error is to add more moderator—a polyethylene sleeve that surrounds the container. A 0.75-in.-thick sleeve with top and bottom plates around a 55-gallon drum of scrap paper completely removes the variation in count rate with the position of the fissile material. How is this possible? The variation in count rate arises in the first place because as high-energy neutrons travel through the moderator they continually lose energy. Fissile material at the container's center captures low-energy neutrons and has a high fission probability whereas material on the container's edge encounters higher-energy neutrons and fissions are less likely. By surrounding the container with some moderator, the first neutron interactions (where energy changes are the largest) are outside the drum. The change in fission probability throughout the container is practically eliminated.

However, this technique must be applied thoughtfully. It is appropriate only if there are finely dispersed waste quantities of fissile material in the drum. But if there are large volumes of high-density fissile material (e.g., uranium metal, U_3O_8), the interior moderator enhances self-shielding and more moderator on the outside will further enhancement it. Adding more moderator would not be a good idea in this case.

Another technique was developed that will work with waste or large masses of fissile material in large containers with a moderating matrix, but without any additional moderator.[7] The container is held stationary during an irradiation and counting sequence; the counts in each bank are stored separately in the computer. The container is then rotated (e.g., by 60°) and a new irradiate-count sequence is performed. This is repeated for a full revolution. The various count rates in the separate detector banks for different orientations of the container are then used to deduce the distribution of fissile material. The spatial resolution need not be great (10 cm for a 55-gallon drum is adequate) and a compromise between resolution and assay time is not hard to find. For a 55-gallon drum with paper and the standard shuffler, an assay time of 30 min. is sufficient. This is about double the usual assay time, but the accuracy of the result may be improved by 50% to 100% for nonuniform distributions. The matrix need not be homogenously distributed, but the matrix distribution should be the same for the calibration and unknown containers. A calibration could be extended to different matrix densities using the flux monitors, as described above.

As previously mentioned, it is possible to calculate accurate calibration count rates. If all the details of the model are correctly described, the accuracy of the result is as good as measured values. This will be discussed further in the section on calibration.

Table V lists some ways to improve accuracy.

C. Sensitivity or Minimum Detectable Mass

What is the smallest fissile mass that can be measured with a high probability (e.g., 95%) that the signal is not just a statistical fluctuation of the noise? That is one way to define sensitivity or, more descriptively, the minimum detectable mass. A shuffler cannot distinguish a delayed neutron from neutrons caused by cosmic-ray interactions or from the stored ^{252}Cf source.

The starting point for calculating the sensitivity is to express it in mathematical terms as the ratio of the delayed neutron counts (called D here) to the total uncertainty in the counts (σ_D here, the 1σ value of a normal distribution, or the standard deviation of a large set of replicated counts). This ratio is set to some number, usually 3 or 4, to express the requirement that the signal be much larger than the fluctuations in the noise. (If $D/\sigma_D = 3$, it is sometimes said that the signal is 3σ over the background.) When the minimum detectable mass, m_s, is present, the delayed neutron counts have the special value of D_s. The two are related through the calibration function, after converting the counts into a rate over a count time T_D.

$$\frac{D_s}{T_D} = f(m_s)\,. \tag{4}$$

TABLE V
Improving Accuracy

To improve accuracy…	But be aware that…
Improve the precision.	See the potential problems given in the table of the previous section.
Use calibration standards that match the items you wish to measure and are known to at least the accuracy you seek for the assays.	These can be expensive and may even be virtually impossible to build.
Control the packaging and the introduction of matrix materials to match your calibration standards.	This may be out of your control, despite your best attempts.
Handle containers of powders (e.g., U_3O_8) in a consistent manner to avoid changing the densities.	Some trial and error with handling techniques may be necessary to discover what works and doesn't work. Changes in density during storage without handling may occur. Training other users will be needed.
Scan larger objects with the ^{252}Cf source during the irradiations to create a distribution of precursors matching the distribution of fissile material.	Some trial and error with scanning techniques may be necessary to find the best one.
Use flux monitors to measure changes in hydrogen (moderator) density.	A measurement program with different moderator densities will be needed to establish the meaning of the flux monitor count rates.
Use the count rates in individual detector banks to find the distribution of fissile material within a large, moderating matrix.	A measurement campaign will be needed to correlate the count rates with the different possible distributions.

The uncertainty in a shuffler's delayed neutron count has a simple expression.[1]

$$\sigma_D = \sqrt{D + B\frac{T_D}{T_B} + B\left(\frac{T_D}{T_B}\right)^2} \quad , \tag{5}$$

where

D = delayed neutron counts (not count rate),
B = background counts (not count rate),
T_D = count time for delayed neutrons, and
T_B = count time for the background.

As is true for all instruments, the sensitivity is limited by the background rate. Shuffler background rates are generally between 10 to 40 counts/s, depending on the shuffler design and the environment in which the shuffler works.

The definition of sensitivity is expressed with D_s/σ_D set to 3 or 4 (usually an integer, but it need not be). The minimum necessary number of delayed neutron counts, D_s, follows from taking the ratio of Eqs. (4) and (5).

$$\frac{D_s}{\sigma_D} = \frac{T_D f(m_s)}{\sqrt{T_D f(m_s) + B\dfrac{T_D}{T_B} + B\left(\dfrac{T_D}{T_B}\right)^2}} . \qquad (6)$$

The minimum detectable mass m_s is found by solving this equation. If the calibration is a straight line through the origin (as for waste quantities), this is easy to do algebraically.[3] For the most complex calibrations Eq. (6) can be solved by numerical methods (such as the Newton-Raphson method).

D. Choosing the Assay Time

In any NDA instrument the assay time is usually a compromise that best meets conflicting specifications. The comparison in Table VI shows more advantages of using long assay times, but in practice rather short assay times (10 to 16 min.) are generally used because throughput is usually the main driver and shorter times do not force us to accept any outrageous disadvantages.

TABLE VI
Assay Times

Advantages of Long Assay Times	**Advantages of Short Assay Times**
Better precision.	Better throughput.
Better sensitivity.	Better immunity to changing conditions (e.g., background)
Can use smaller ^{252}Cf masses for a given precision, reducing cost and shuffler size.	
Can use smaller detection efficiencies for a given precision, reducing cost.	

Equation (6) is a good way to estimate the assay time needed to reach a measurement goal. The background and delayed neutron count rate must be known as well as possible. The latter depends on the ^{252}Cf mass, so there are many factors linked together. These will be spelled out in detail in a later section on designing a shuffler.

As a general rule of thumb, about a quarter of the assay time is spent on a background count. If the background rate is much different than the 10 to 40 counts/s mentioned earlier, a new study should be made of the fraction of total time spent on background counting. It is possible to do one long background count and use it for all assays of the day (or more) if it is clear that the background rate will not change. This would be the most efficient use of all the time available, but it is rarely done for shufflers because it is not certain that the background rate is constant. The background rate was *not* measured with each assay for the Liquid Raffinate Shuffler because the assay time had to be a short as possible (100 s) to ensure catching a high ^{235}U concentration as quickly as possible. A background count was taken periodically and used for many succeeding assays.

Los Alamos shufflers have always used an assay time set before the assay begins, expressed through the background time and the various parameters defining the shuffles. An alternative is to terminate the assay when a desired relative precision has been reached, up to some maximum number of shuffles. The average count rate then should be adjusted for the difference in the number of shuffles just used and the number used during calibration. This is another source of inaccuracy that is easily avoided by using a fixed assay time.

III. CREATING A SHUFFLER

A. Basic components

1. Hardware

a. Mechanical (Including the ^{252}Cf Source)

A shuffler's design centers on the assay chamber, which must be large enough to hold the biggest container, but no bigger than necessary. Empty space around a container means that neutrons may pass through the assay chamber with zero probability of causing a fission and the size of the ^{252}Cf source must be increased accordingly. This leads to the need for a larger storage block for the source, which adds more weight and more cost to the shuffler. A snug fit between the assay chamber and the objects to be assayed is the ideal, but even a small can may be quite adequately assayed in the large 55-gallon-drum shuffler despite the unequal sizes. While a 55-gallon drum nicely fills the assay chamber, the fissile material may occupy only a small portion of the drum, so most neutrons never encounter the fissile material anyway.

Many containers should be rotated during an assay to make the irradiation more uniform throughout their volumes. The 55-gallon-drum shufflers have always had turntables, but their use is a software option (which is normally used). The Scrap Shuffler rotated the large cans of metal pieces, but the Billet Shuffler did not rotate the billets because the ^{252}Cf source went through a hole in the central axis.

The ^{252}Cf source needs a storage block to reduce the dose rate from the source to the level specified by the user. An unrealistic specification will be uncovered early in the design. Obviously, a stronger source requires a larger shield; the details of this relationship will be discussed in a later section. In the standard 55-gallon-drum shuffler, the storage block is positioned above the assay chamber, but this is not the only possible placement. In the Billet Shuffler, the storage block is positioned to one side of the assay chamber. In the two waste-container shufflers built for Savannah River, the source is stored in the ground below the assay chamber. The best storage option for each shuffler has to be decided on a case-by-case basis and is usually driven more by facility issues than by physics issues.

In Los Alamos shufflers, the ^{252}Cf source is moved with a stepping motor that drives a cable attached to the source; positioning is done quickly and accurately. Los Alamos uses motors and accessories from Compumotor, which have been very reliable and easy to interface with a computer. An alternative used in European shufflers is to drive the source pneumatically. This is a fast method, but it can place the source at only one of two positions and cannot be used for scanning. Pneumatic methods seem to have been dropped in favor of stepping motors.

Stepping motors need overtravel sensors that can quickly send shutdown signals in case of a malfunction. Los Alamos shufflers typically use three metal proximity switches to assist the stepping motor. These switches respond to the presence or absence of the free end of the flexible cable driven by the motor. Two are for overtravel protection, but are rarely used because of the high reliability of the motion system. An overtravel would cause an assay to be aborted and an error message to be generated. The third proximity switch corresponds to the stored position of the ^{252}Cf source. When the source is properly stored (in a shielding block, at the correct depth underground, etc.), the free end of the cable is very close to the center of the proximity switch. The switch also serves as the starting point for the next high-speed transfer of the source into the assay chamber. The tip of the cable is always checked and, if need be, put at this starting position before a high-speed transfer. This makes the irradiation more reproducible (helping the precision and accuracy) and also ensures that there is no buildup of positioning errors that could send the source into a mechanical stop at high speed. The capsule containing the source is made almost entirely of solid steel and cannot be damaged by the shuffler and the motor has overload protection, but the drive gear could be damaged by a cable that stops suddenly before the motor does.

A fourth proximity switch is used to verify that the turntable is turning when it should be and to help orient it correctly at the end of an assay. This switch responds to a protruding bolt head that passes once every revolution (once every 20 s or so). If the software does not see this signal within a preset time, it assumes the turntable is stationary and aborts the assay.

In a couple of early (c. 1975) shufflers, a fission chamber was put near the source's store position. This gave a direct indication that the source was in fact stored, but the main purpose was to check the system date in the computer. This date is important because it is used to correct measured count rates for the steady decay of the source; if the system date is wrong, the assay will be wrong. The fission chamber records a count rate that can be predicted after it is measured during the source's installation. If the predicted rate is wrong, it is likely that the system's date is wrong and should be checked. This introduced added complexity into the hardware, electronics, and software, and has not been used in succeeding shufflers. The system date now is checked by routine measurement controls done by a facility. The other function of giving a direct indication of the source being stored has more merit; the section on safety features will describe the equivalent signals used today without the fission chamber.

b. Electrical

The assay chamber is surrounded by neutron detectors, which are ^{3}He tubes from Reuter-Stokes with 1-in. diameters and pressures of 4 atm. There is nothing sacred about these particular parameters for shufflers, but this type of tube is widely used in Los Alamos safeguards instruments. For higher detection efficiency, the gas pressure can be as much as 10 atm.

The tubes are electronically grouped and one signal cable receives the signals from several detectors, usually by connecting a set of detectors to one amplifier. The Solid-Waste Shuffler at Dounreay, Scotland, has an amplifier for each tube to avoid problems with intense gamma rays from fission products. There are only eight tubes, so the cost disadvantage is small. The standard 55-gallon-drum shuffler has six banks of detectors surrounding the side of the assay chamber, plus a bank above and a bank below the chamber. A tube was omitted from the center of the bottom bank to make room for the shaft of the turntable to pass through to the rotation motor below the bank. This missing tube and the heavy metal turntable above the detector bank make the bottom detector bank less efficient than the top bank. This configuration also introduces an asymmetry that should be addressed in future designs.

The amplifiers used for many years are a Los Alamos design now commercially available and built around the AmpTek 111 amplifier.

Flux monitors are also Reuter-Stokes ^{3}He tubes, but are made less efficient to keep their interactions at a high but acceptable rate while the ^{252}Cf source is nearby. This inefficiency is accomplished by reducing the gas pressure, reducing the diameter, reducing the length, or some combination of these.

All of these detectors and amplifiers are connected to other electronic components in a rack. Off-the-shelf equipment is used as much as possible, but some custom-built units are necessary. The rack typically has the following contents:

- A NIM bin holds high-voltage supplies (up to 2 kV), low-voltage supplies (5 V), a 12-channel scaler (Los Alamos-designed but now available from Canberra), a custom signal display NIM for the cable and turntable proximity switches, a custom signal display NIM that shows an operator whether the door may be opened or not (according to whether the source is in use or not), and possibly a custom switch to choose between active and passive assays.
- A Compumotor Indexer receives high-level commands from the computer and translates them into low-level commands to the motor. The Indexer also has parallel ports for input and output that are used to accept signals from the proximity switches and to set lamps, respectively.
- If an analog turntable motor is used, a custom driver for it will be in the rack. If a stepping motor is used, there is no additional motor equipment in the rack because the Indexer drives it.
- The standard 55-gallon-drum shuffler has a coincidence counter for passive counting. It shares a computer serial port with the 12-channel scaler through a switch.
- The system computer, monitor, and keyboard may be built into the rack, or placed on a nearby desk.
- A fan or even an air conditioner may be needed as part of the rack, according to the environmental conditions.
- A power-line conditioner may be placed in the rack for those facilities with unstable lines.
- An uninterruptible power supply (UPS) can be inside or outside the rack, or not used at all. Some facilities want enough backup power to complete an assay and have the ^{252}Cf source stored before a UPS is drained. The alternative is to keep the shuffler's door(s) closed when there is a power outage; the source will be shielded regardless of the position it was in when power was lost.

Some miscellaneous electrical equipment completes the survey. The Compumotor stepping motor has a driver box that must be located close to the motor, so it usually cannot be placed in the rack. If there is a turntable, both analog and stepping motors have been used. The analog motors are simple but require a custom-made control unit and the range of speed is adequate but limited. The stepping motor needs no custom electronics, the range of speed is large, and the control of the speed and orientation is very precise. The analog motor system is usually entirely satisfactory, but for some applications only the stepping motor will provide the control needed. In either case, the motor is connected to the turntable's shaft by a motorcycle chain and gears.

We have gone through various Compumotor Indexer models as they have evolved from the company. The standard 55-gallon-drum shuffler has used the Model 4000. This can drive up to four stepping motors and we have used as many as three in a single shuffler: one for the ^{252}Cf source, another for the turntable, and a third for a second (weak) ^{252}Cf source for performing add-a-source matrix corrections as part of passive assays. The Model 4000 also has a four-line liquid-crystal display that continuously shows the input and output bits of the Indexer's parallel ports and the number of steps taken by the main ^{252}Cf source. This latter number shows changes in the source's position (in motor steps, which are 625 to the inch).

The Los Alamos 12-channel scaler was created because no commercial scaler was available with the same convenient features. Channels 1 through 11 are individual inputs, each with its own memory to count the pulses received. Channel 0's function is set by an internal jumper and is either a 12th input or combination of an internal 10 kHz clock with an output that passes the sum of the pulses from the other 11 channels. Only the second option is used by shufflers. The 10 kHz clock is used to time the various actions during the shuffles to 0.1 ms (times to move the source, irradiate, and count delayed neutrons) and the summed output is used for passive measurements with the output going to a coincidence (or multiplicity) analyzer. Each channel has an LED lamp that flashes for each pulse received, until at high rates it saturates and shines steadily. The lamp for channel 0 is on steadily because it cannot flash at 10 kHz. The slow, irregular flickering with the source stored is the normal background rate. With the ^{252}Cf source in (or only near) the assay chamber, the lamps shine brightly and steadily. Not all channels are likely to be used, so the lamps of unused channels remain dark. The lamps of flux monitors will have very slow (almost zero) rates of flashing from background causes.

The custom-made status display NIM shows the responses from the proximity switches (cable, turntable, and door) and whether or not a measurement is in progress. This helps to ensure that the shuffler is operating properly and to debug problems, but the everyday application is safety assurance for the users. The position of the ^{252}Cf source is of special interest and the lamp corresponding to the store position should be checked before opening the door(s) to the assay chamber. If that lamp is on, the free end of the cable is on the store proximity switch and the source is in the center of the shield. If the reverse overtravel sensor is also on, the cable has overshot the store switch by about 4 in. and the source is 4 in. away from the ideal position, but is still safely stored. If the lamp for the store switch is not on, the position of the source is unknown and the doors should not be opened until the situation is understood and corrected. A glance at the lamps on the 12-channel scaler will show if the source is more than a few inches away from its store position because as the source approaches the assay chamber these lamps first flicker vigorously and then shine steadily. These issues are discussed in more detail in the section on safety features.

The standard 55-gallon-drum shuffler has a simple switch mounted on a NIM front panel for the purpose of routing an RS-232 line from the computer to either the 12-channel scaler or a coincidence electronics unit. (This is usually the Los Alamos-designed Canberra JSR-12, but it could be a multiplicity unit.) If the switch is in the wrong position, the software will fail to find the hardware it seeks and the user will be alerted. It is impossible to operate the shuffler with the switch in the wrong position. The switch uses no power from the NIM bin and is mounted there because it is a convenient location. Figure 26 shows the electronic connections among the various shuffler components, with the coincidence counter as an optional feature.

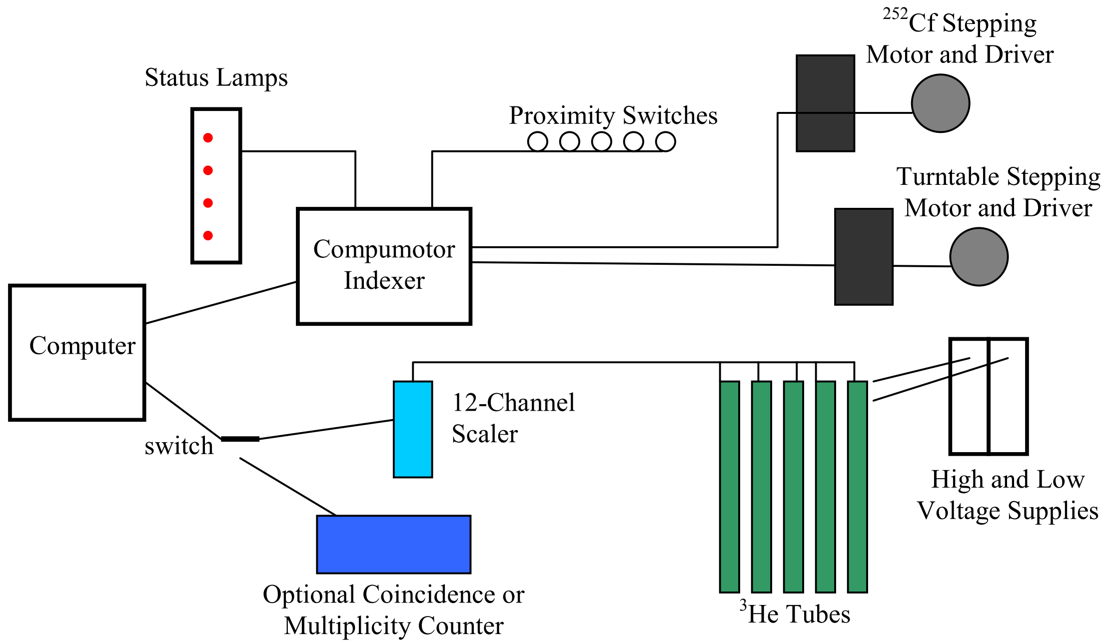


Fig. 26. The electrical connections among shuffler components. A serial data line from the computer normally goes to a 12-channel scaler, but for passive counting it is switched to a coincidence or multiplicity counter.

The computers used in shufflers have followed the evolution of computers themselves. Various DEC models and the FORTRAN language were used in the 1970s and into the 1980s. Then DOS-based machines and C were used from the late 1980s to the mid-1990s. Currently, the computers use a Windows variant and Visual C++. The basic operations and the results are independent of the platform chosen. The mathematical algorithms in the data analysis have been virtually unchanged throughout. Some computers and printers were built into the electronics rack, but because operating systems require the use of a mouse or trackball, computers have migrated to a table adjacent to the rack. A facility's preference for the placement of the computer and printer can readily be accommodated.

The environment of the room in which the electronics must reside is important. Many electronics units are specified for no more than 80° F (27° C) and noncondensing humidity. Circulating fans or air conditioners for racks have not been needed in these conditions, but for room temperatures above this limit, circulating fans have been used. The racks for several shufflers in more brutal, uncontrolled conditions have been cooled with air conditioners.

The relative humidity surrounding the amplifier boards for the detector tubes is important because high humidity can encourage high-voltage arcing. The amplifiers are sealed inside a metal junction box using an O-ring under the lid, but there are still slow leaks into the box through the connectors for the high-voltage, low-voltage, and signal cables. Desiccant capsules are usually built into the junction box walls and can be easily unscrewed and replaced. For some locations, the humidity is not high enough to require desiccants. Where the humidity approaches 100% for weeks or more at a time, the desiccants are very important. Arcing is not difficult to detect because the noise appears as an increase to the background rate and may occur irregularly.

A power-line conditioner and UPS are options chosen to match facility conditions and requirements. They help protect the shuffler's hardware and, therefore, increase its reliability. A conditioner is commonly used, but a UPS is rare.

2. Software

The shuffler's computer can run two entirely separate codes: the shuffler code (described in detail below) and the INCC code for performing passive assays (which will not be discussed). The Compumotor Indexer has a small code used for executing sequences of action, but because it is specific to the computer's hardware and may change as models change, it won't be discussed.

The extensive shuffler software controls the hardware and analyzes the neutron counts. Users can control the software's actions to the extent of setting important parameters and initiating measurement sequences, but the basic actions during a measurement are still performed automatically by the computer. Qualified users can also perform diagnostic tests of individual components.

There are a few specialized actions that the Compumotor Indexer will perform that are not initiated by the computer; in fact, the computer need not even be running. The most important of these actions is rapidly returning the ^{252}Cf source to its store position if the shuffler's door is open when the source is not stored. (The next section will elaborate on this and other safety features.) The Indexer will also abort a movement of the source if an overtravel sensor is reached. This helps protect the stepping motor and driver from damage, although the driver also has internal electrical overload protection. These autonomous actions by the Indexer include signals to the shuffler's computer that these anomalous events have occurred. If the computer is running its shuffler software, it will abort that assay and inform the user of the event, but if the computer is not running, the Indexer's actions are still taken.

The shuffler's computer software has several standard features. They are usually divided into two or three categories, each requiring different levels of passwords to access. Custom features may be added for special conditions, but will not be discussed here.

- Perform assays, calibration measurements (giving count rates but not masses), precision measurements (repeated), bias checks (measurements on well-known standards), and so-called standard checks (check the empty assay chamber for holdup and then do a bias check with a standard item).
- Assign passwords and levels of access to software features.
- Perform an interactive safety check to confirm that all proximity switches and lamps are working properly.
- Review archived results (showing a number of the most recently completed measurements or those measurements between two dates).
- Assign "general" parameters that are common to all measurements.
    - Nuclear constants: half-lives and delayed neutron yields for the six groups of precursor nuclei; the half-life of ^{252}Cf; and the reference date for the ^{252}Cf source that establishes the constant ^{252}Cf mass that is used for all the assays.
    - Compumotor input-output bit assignments; which bit controls which lamp and which bit corresponds to which proximity switch.
    - The maximum number of measurements that can be archived. (This parameter was important before hard drives with immense capacity became commonplace.)
    - Names of types of items that might be measured.
    - Bias and precision check parameters: the number of repeated measurements to perform; the decay time to use between measurements; the expected assay result and the expected uncertainty; and confidence levels to apply to the results.
    - Expected results from the standard check to which the measurements are compared.
- Assign "item-specific" parameters, one set for each container size and material type to be measured. Each type of item has a unique name given in the general parameters.
    - Assay parameters: distances, speeds, accelerations, and pauses used in performing an irradiation; the length of the background count; and whether or not to rotate the turntable and to use the flux monitors. Each type of item can be assayed in a unique manner (e.g., large-mass items can be measured in less time than small-small items).
    - Assay diagnostics: the expected ratio of counts in designated pairs of detector banks (as a check that they are operating properly, but applied only as an option); the accepted percent deviation from unity of a number calculated by comparing expected and measured motions of the ^{252}Cf source (checking for repeatability during shuffles and applying a correction if necessary); and a parameter to correct for dead-time losses in the flux monitors (not strictly an assay diagnostic). A dedicated diagnostic checks that no detector bank has a count of zero, which is taken to be an error, resulting in an aborted measurement. Furthermore, if there is an internal problem, error messages are given on the monitor.
    - Normalization parameter: a number with an uncertainty that multiplies the count rate just before the calibration is applied to produce the fissile material mass; this number is always exactly unity with no uncertainty unless there is some special reason to change it.
    - Calibration parameters: Each item type has its own calibration parameters with a set of variances and covariances. The standard expression provided is a third-order polynomial, but each item type

(as an option) can have more than one set of parameters for different ^{235}U enrichments. Interpolations on the enrichment are done among these polynomials to get the ^{235}U mass for the enrichment specified by the user.

- Bias correction parameters: the mass from the calibration curve is multiplied by a second-order polynomial whose parameters are set to correct for any known bias. In practice, this has always been set to make no correction (the mass is multiplied by unity), but the option is made available for special cases. For example, a fixed contamination of the assay chamber would require a bias correction.
- Download the Compumotor Indexer's code into the Indexer. This is done rarely because the Indexer remembers its code even when the power is turned off.
- Diagnostics: This is a set of "primitive" actions that can be performed to check specific shuffler components.
  - Move the ^{252}Cf source a specified number of motor steps. Most shufflers have 625 motor steps per inch. By using a small number of steps, the communications link and the drive motor system can be checked safely. The source can also be positioned to induce pulses from the detectors to check their functions.
  - Store the Cf source. This one-button command quickly and safely puts the source in its store position, starting from an arbitrary, unknown distance from the store position. This is done by moving the source toward the store position 4 in. at a time. Another step toward the store position is taken only if the store switch has not been reached. After it is reached, a series of smaller steps are quickly taken in alternating directions with decreasing distances until the free end of the cable is centered on the switch.
  - Test door proximity switch. The user is guided through the sequence of opening and closing the door to exercise the switch. This is a portion of the safety check available from the main menu.
  - Test Cf proximity switches. The source is moved until the proximity switches are (or should be) reached to exercise them. This is a portion of the safety check.
  - Test status lamps. The user is guided through a sequence that turns lamps on and off individually to test their operation. This is a portion of the safety check.
  - Move Cf to test position. The source is moved to a standard position that generates counts from the banks without saturating them. The count rate can be taken and compared to historical values, taking into account the decay of the source.
  - Count with no Cf motion. The scaler is cleared and then counts for the user's preset time for both the delayed neutron and flux monitor detectors. The sum of the delayed neutrons and the count rate are usually displayed for convenience. The operation of the detectors can easily be checked with this option.
  - Test rotation motor. The turntable's motor can be turned on and off with this option.
  - Set parallel bits. The lamps and other status displays can be toggled by changing the bits on the Indexer's parallel output. For shufflers with analog turntable motors, one of the bits will also start and stop the motor.
  - Write ASCII data. An ASCII file can be written at the end of a measurement that contains all the counts and times, as well as a header that identifies the measurement (date, time, facility, item ID, etc.). This detailed archive file can be used to reanalyze the data with different calibrations. The user controls whether this option is exercised or not.
  - Type of printout. Three different printouts, each showing a different level of detail, can be generated after a measurement. The short printout gives a few lines containing the result and basic information like date, time, facility, and item ID. A long printout shows every possible number (counts, times, intermediate calculations, calibration parameters, etc.) from every shuffle and takes up many pages. The medium printout is about two pages long and skips the values from every shuffle and just gives their sums. The diagnostic value of archived printouts is immense; if the shuffler's operation is in any way suspect, a comparison of current and old printouts will resolve questions and point to solutions.
  - Print last results. If a short printout was selected but more information is needed, a medium or long printout can be created *before* the information is erased from the computer's memory,

either by exiting the code or by taking another measurement. Otherwise, the ASCII file of data can be used to generate new printouts.

Today's software is written in Visual C++ and has a familiar "look and feel" to regular computer users. Older software might still be found in FORTRAN and C, using the menu styles ("pick lists") of those eras. Regardless of the operating system and programming language, the shufflers do fundamentally the same things in the same way. Most importantly, the data analysis code has been stable for more than a decade and the assay results are independent of the computer used.

Some specialized shufflers require custom features to operate the complete system, but the same data analysis is used in all cases. The Liquid Raffinate Shuffler received information from a flow meter to make an adjustment to the assay result for varying flow rates. The shuffler for spent navel fuel assemblies could control a hoist and perform an assay in either of two assay chambers (one for the fuel, another for waste canisters). Two Savannah River shufflers had two motorized doors (input and output) with emergency stop strips, and one of these had a conveyer system that was under the shuffler's control and a strain-gauge scale to weigh the items while on the turntable. Such features are important facility needs, but do not affect the basic nature of the shuffler operation.

3. Safety features

The most novel hazards associated with shufflers arise from the ^{252}Cf sources. The masses of these sources have ranged from 1 to 3000 µg, according to the measurement problem. A microgram is a small mass, but if the source is unshielded, the dose rate at one meter is 2.5 mrem/hr. The standard 55-gallon-drum shuffler may have as much as 550 µg of ^{252}Cf that delivers 1100 mrem/hr at one meter if unshielded. Clearly, the shuffler must be designed to keep the source shielded at all times. A complete list of safety features follows.

- The guide tube for the flexible cable attached to the source is closed on the ends to trap the cable and source within it and the shielding. The end of the tube where the free end of the cable may reach is usually sealed by a bolt in the end of a metal block that holds the reverse overtravel proximity switch. The other end of the guide tube usually has a short air gap just beyond the bottom of the assay chamber or some other rigid metal object. Segments of the tube are held rigid by clamps and joined with Swagelok connectors. The ^{252}Cf source is trapped within the tube, which in turn is within shielding, so if the shuffler's door is closed, the source is always within shielding from either the storage block or the assay chamber.
- If the source is not precisely stored (to within 0.1 in. or so) when the door to the assay chamber is opened, the Indexer will automatically return the source to the store position within a few seconds. The computer is not involved and need not even be on or connected to the Indexer. The proximity switch on the door is sensitive enough to indicate when the latch has simply been loosened, even though the door may seem closed. The door is usually heavy (1000 pounds for the standard 55-gallon-drum shuffler) and takes several seconds to open. Even if the door is opened while the source is as far from the store position as possible, by the time the door is pulled open the source will be out of the assay chamber and rapidly approaching the store position. Any small dose to the person near the door will be lost in the noise of the daily background dose. Even if there were no shielding and a person was a meter from the source for 10 s, the dose from 550 µg would be only 3.8 mrem. No one opening a shuffler door will receive anything close to this dose while the Indexer is running its internal code.

  Obviously, for the Indexer and the motor driver to perform their automatic response, they must be powered on. When power is restored after an outage, the Indexer recovers and automatically starts running its program. This is an important reason to keep the power on to these important hardware items.
- If the assay chamber door is not closed and securely latched, the Indexer cannot move the ^{252}Cf source from its store position. The proximity switch on the door is read and serves as an interlock to prevent moving the source away from the store position unless the door is closed.
- The powered stepping (and servo) motors cannot move without being given the proper signals from their Compumotor drivers. The holding torques of these motors are much too high for a human or gravity to be able to move such a motor. Even with the power off, it is unlikely that gravity will pull a ^{252}Cf source from its store position. Friction between the long cable attached to the source and its guide tube is enough to prevent slippage. The prudent action is to keep the motor powered, even if the rack and computer are off, because the holding torque will lock the source in position.
- The amount of shielding needed is specific to the facility. Maximum dose rates on the surface of a shuffler are generally specified by the facility and have been lowered from the early days of shufflers. The older limits were 5 mrem/hr in contact with the shuffler; more recently, 0.5 mrem/hr has been the standard.

A factor of 10 reduction in dose rate can mean a big increase in the thickness of the shielding and hence the size of the shuffler. There is no single number to express the increase because it depends on the mass of the ^{252}Cf involved. More technical shielding information will be given in a later section.

One way to reduce dose rates without increasing costs is to use a barrier that increases the distance from the shuffler's surface to people. This may be a few inches or a few feet. For example, if the dose rate on the surface of a storage block 2 ft. thick is 0.6 mrem/hr, a barrier of only 2 inches beyond the shuffler's surface will have a dose of 0.5 mrem/hr on its surface. (These numbers are for the Billet Shuffler.)

There is never any good reason to "hug" a shuffler during measurements, so the surface dose rate is not really applicable to users. But it is easy to measure and encompasses the worst case of a user who might become unusually attached to the hardware.

- A user should understand what the status lamps mean. They are also useful in diagnosing anomalies. Lamps show the status of the proximity switches that relate to the current location of the ^{252}Cf source, the door, and the turntable (if there is one), as well as if a measurement is in progress. The lamps on the 12-channel scaler show if a neutron source is inside the assay chamber.

  If a lamp shows that the source is not stored and the lamps of the scaler are brightly lit, the indications are strong that the source is either in or near the assay chamber. If users are not prepared for anomaly management, they should leave the door closed and go for help. Otherwise, the latch on the door can be loosened a bit so that the door's proximity switch will toggle and the Indexer will automatically store the source. If this does not work and the Indexer is on and running, there is a malfunction, and the doors should be kept closed while the situation is examined and corrected.

  Note that putting a kilogram or so of plutonium in the assay chamber will also make the lamps of the scaler glow brightly—this is caused by the spontaneous fissions of plutonium and not the ^{252}Cf. The store lamp alone will indicate whether or not the source is stored.
- The Indexer has a liquid-crystal display that shows the bit patterns on the input and output parallel ports. The knowledgeable user can compare the bits' values with the status lamps when there is reason to double check a lamp reading. The bits are set by the signals that are also sent to the lamps, so they should always agree.

B. Physics Design

The design of a shuffler starts with a thorough understanding of the needs of the ultimate user. This process involves listening to the user, asking questions of the user, and sending a written summary to all concerned parties (facility managers, facility safety and security officers, etc.). It may be impossible to avoid all misunderstandings and last-minute impositions of new requirements, but as many should be avoided as possible.

The physics design defines parameters that will ensure the shuffler meets the performance specifications. It is a paper and computer study that is done before any design drawings are made. The gross features of the design are defined by the physics calculations.

1. User Specifications

Table VII gives an extensive set of questions that should be studied by the facility personnel and shuffler designers together. They can be rather specific (e.g., "Is ^{232}Th present?") to bring to the fore something the facility may not have thought was important.

TABLE VII
Shuffler Specifications

Topic	Questions	Interacts with…
Important Isotopes	What isotopes are to be measured among what other isotopes? ^{235}U? What enrichment? Pu present? ^{239}Pu? Why not passive counting? What Pu isotopics? What other isotopes (e.g., ^{244}Cm)? ^{237}Np? ^{233}U? ^{232}Th? ^{241}Am? What is the origin of the material? Were impurities introduced (especially moderators like H and C, and absorbers like B and Cd in the presence of moderators)? If the material is a strong alpha emitter (like Pu), are there light elements (especially, F, Li, O, and Al) present that will increase the background rate through (α,n) reactions?	Packaging. Measurement Performance.
Mass Range	What is the mass range for the important isotope(s)?	Measurement Performance. The ^{252}Cf Mass.
Packaging	How will the materials be packaged? What are the sizes and shapes of the packages? How much hydrogenous material will be present?	Important Isotopes. The ^{252}Cf Mass.
Measurement Performance	What is the minimum mass of the important isotope(s) to be measured? What is the desired precision and accuracy? (These terms should have operational definitions to avoid confusion now and later.) What measurement time will be allowed to reach these goals? What calibration standards will be used to achieve the measurement goals? Where will these standards be made and who will certify them? What throughput (measurement and handling time) is necessary?	Important Isotopes. The ^{252}Cf Mass. Personnel Shielding.
The ^{252}Cf Mass and Shielding	How many years of use are needed from a single ^{252}Cf source, given its 2.65 year half-life? (Note that a source may no longer be strong enough to meet the requirements for the smallest masses but could still work for the larger masses, and with longer assay times it could still work for the smaller masses.) What are the requirements on the dose rate outside the shuffler from the source? (Note that lower dose rates require more shielding or a smaller source that then may force a longer assay time to meet the measurement performance requirements.) Can the source be stored in the ground below the shuffler? If so, there is a big savings in cost and space.	Mass Range. Packaging. Measurement Performance. The Shuffler's Environment. Personnel Shielding.
The Shuffler's Neutron Environment	What other neutron or gamma-ray instruments, including portal monitors, are near (within 50 feet) the shuffler? What shielding exists between the shuffler and these other instruments? What other sources of neutrons are near the shuffler? Are there any storage vaults with Pu, neutron generators, etc.? Will neutron-emitting material be moving in the vicinity of the shuffler during measurements? A changing background rate is hard on accuracy. What is the elevation above sea level? An estimate of the cosmic-ray background rate needs this information.	The ^{252}Cf Mass. Measurement Performance.
Personnel Shielding	What is the maximum gamma-ray and maximum neutron dose rate acceptable by the facility? Where on the shuffler and how will these dose rates be measured?	The ^{252}Cf Mass. Measurement Performance.
Installation Issues	What is the space available to the shuffler? What is the path and doorways through which pieces of the shuffler must pass to reach the installation space? What electrical outlets, heating, and air conditioning is or will be installed?	
Auxiliary Equipment	Will the shuffler software control auxiliary equipment (e.g., conveyor, security alarm, hoist)?	

The purpose of the third column is to stress that the topics in the first column are interrelated. Usually a compromise has to be found to best satisfy competing requirements. For example, a large ^{252}Cf mass will always help the measurement performance, but it will increase the size and cost of the personnel shielding and might interfere more with nearby instruments. It might be desirable to measure material inside some package that doesn't transport neutrons well, but the ^{252}Cf mass needed could be unrealistically large. If the shuffler normally measured large masses of ^{235}U, why not use it for the occasional capsule containing a few grams of ^{237}Np? The uranium might need only a small ^{252}Cf mass, but the neptunium will require a much larger mass. Do you build a large, expensive shuffler with a large source just so you can use it once every 5 years for neptunium? Or do you build a smaller, less-expensive shuffler that is fine for uranium but requires a 12-hour measurement on a few grams of neptunium?

Some of the special features and auxiliary equipment in Los Alamos shufflers are listed below. Most do not affect the assay results, but better integrate the shuffler into the facility.

- A conveyor system ran through a shuffler's assay chamber, using both input and output doors on opposite sides of the chamber. The conveyor's controller accepted signals from and sent status signals to the shuffler's software.
- A scale was integrated into the assay chamber to weigh the container being assayed.
- A hoist was controlled by the shuffler's software to position the material being measured.
- A flow meter's output was accepted by a shuffler to adjust the measurements for different flow rates of liquids passing through the assay chamber.
- Status lamps were duplicated near the shuffler's door to better catch a user's eyes.
- Special gamma-ray shielding and amplifiers were used to prevent highly intense gamma rays from inducing reactions in the ^{3}He neutron detector tubes.

2. Minimum Delayed Neutron Count Rate

The next step in the physics design is to calculate the minimum delayed neutron count rate that will meet the performance specifications. The set of specifications can be summarized by a sentence such as "Measure a 500 g sphere of 94% enriched ^{235}U metal with 1% relative precision in 1000 s." The material has been specified along with the precision and assay time. In this section, only the relative precision and assay time are needed. The material description will be used in the next section.

If there are no background counts, the relative precision of a delayed neutron count D is $1/\sqrt{D}$. For 1% relative precision, D is 10,000 counts. The full 1000 s could be devoted to this count, so the minimum count rate needed is a leisurely 10 counts/s. The ^{252}Cf source needed for this case would be relatively small and will be calculated in a later section.

But having no background counts is not realistic. Cosmic-ray interactions can be reduced by shielding (including shielding by the atmosphere), and the neutrons leaking into the assay chamber from the ^{252}Cf source can be reduced by even more shielding. How much are you willing to pay in cost and space for a reduced background rate?[7] No shuffler has ever taken any special measures to reduce cosmic-ray-induced neutrons, and typical background rates from cosmic rays are 15 counts/s to nearly zero. Leakage from the ^{252}Cf storage block may add another 15 counts/s or less. Background rates of 30 counts/s are not unusual, but they have also been lower. The minimum count rate needed is D_s/T_c, as given in Eq. (4). The relative precision is the ratio of the count's uncertainty with the count, as given in Eq. (6).

For the example given above and a background rate of 30 counts/s, the relative precision is 1% after a 270-s background count and a 240-s delayed neutron count when D is 17,688 counts. This typical background rate has forced us to count about 77% more delayed neutrons to reach the same relative precision. This count (and the corresponding 73.7 counts/s) is not unusual, and is in fact routine for the shuffler to produce, but the right ^{252}Cf mass must be chosen, and that is the next step.

So far we have not needed to know anything about the material or the shuffler design; we have only performed a statistical calculation. The hardest part of this step can be estimating the background rate, B/T_b. If the new shuffler design is a modification of an existing design and the environment of the new location is understood, a good estimate of the background rate can be made based on experience. Otherwise, the best estimate increased by a conservative safety margin must be made.

3. The Minimum ^{252}Cf Mass, Detection Efficiency, and Assay Chamber Shape

The rest of the shuffler's design depends on the mass of the ^{252}Cf that is needed to generate the minimum count rate needed to meet the measurement specifications. What is the smallest mass that will provide the desired relative precision in the time allowed? The detection efficiency is also directly involved at this point and the shape of the assay chamber has a role in determining it. But neither of these can be known accurately without a detailed design. An iterative process can be applied. With some experience, only a single pass through the process may be needed.

Pick a plausible detection efficiency for the first iteration. Something close to 20% is common for shufflers with a single layer of comfortably spaced ^{3}He tubes in polyethylene, but as much as 60%, could be achieved with multiple layers of tubes. The energy spectrum for delayed neutrons should be used, not the spectrum for ^{252}Cf or other prompt neutrons.

Pick an approximate size and shape for the assay chamber. If the final shape will snugly fit around the container (e.g., cylindrical), a looser fit (e.g., rectangular) will lead to a larger answer for the minimum ^{252}Cf mass. If the object does not have axial symmetry, several orientations of it (as if the object were being rotated during irradiations) should be used in calculations to get an average.

Next, calculate the probability that a single neutron from the ^{252}Cf source will induce a fission in the specified material, using the provisional assay chamber. It is difficult to do this accurately without a Monte Carlo simulation because the probability of inducing a fission is a function of neutron energy. There is a wide range of neutron energies from the source that gets even more complex through interactions with the walls of the assay chamber and the material being measured. The source may not be stationary during the irradiation and so the neutron flux at different energies also can be a function of time. A complex, detailed model made at this early stage likely will have to be redone later, so a compromise should be sought that will give enough information to lead to a detailed design with which a new round of simulations may be done.

A detailed model of a portion of the shuffler may be needed early on if the specifications call for an insensitivity to the enrichment of uranium or the isotopics of some other element. In this case, spectrum tailoring may be done to avoid fissioning isotopes like ^{238}U. The ^{252}Cf source is surrounded by carefully chosen materials to reduce the neutrons' energies below a threshold energy (1 MeV for ^{238}U). This lowers the probability that a neutron will enter the assay chamber, but also increases the fission probability after a neutron enters the assay chamber, so the overall effect should be calculated carefully.

The Los Alamos Monte Carlo code MCNP has been successfully used to calculate the fission probabilities for shufflers at Los Alamos and in Europe. A proven code uses continuous analog techniques to track neutron interactions within the shuffler's materials, so changes in energy of the neutrons are correctly taken into account.

Assume that a model of the shuffler and a 500 g sphere of uranium have been made and the calculated fission probability is 7.89×10^{-4} fission per ^{252}Cf neutron. This includes fissions caused by fission neutrons as well as ^{252}Cf neutrons (if the "NONU" line is not used in the MCNP file). The average number of neutrons released from a fission is known for all the fissile materials of interest to safeguards (for ^{235}U this is about 2.43). The average ^{252}Cf neutron produces 1.92×10^{-3} fission neutrons, but only a small fraction of these neutrons are delayed. In the case of ^{235}U, that fraction is about 1.6%, so the average ^{252}Cf neutron produces 3.07×10^{-5} delayed neutrons.

The detection efficiency can be calculated with MCNP for a specified array of ^{3}He tubes. Neutrons with the energy spectrum of delayed neutrons are started throughout the fissile material (perhaps matching the locations where fissions were previously calculated, perhaps using a uniform distribution) and then tracked to find the probability of causing ^{3}He(n,p)^{3}H reactions. For our example, assume the result is 24%.

Some delayed neutrons are released while the ^{252}Cf irradiation is still in progress. These cannot be distinguished from the many, many neutrons from ^{252}Cf, and therefore do not contribute to the count we seek. The fraction of neutrons that can be counted while the ^{252}Cf source is stored depends on the irradiation scheme. A 20% fraction is a representative value and will be assumed here. This fraction can be calculated from a set of times for the different stages of a shuffle and the number of shuffles.[1]

The average ^{252}Cf neutron has the following probability of leading to a delayed neutron (dn) count:

$$(3.07 \times 10^{-5}\ \text{dn}/^{252}\text{Cf n})(0.24\ \text{reaction/dn})(0.20\text{count/reaction}) = 1.47 \times 10^{-6}\ \text{count/Cf n}.$$

If the ^{252}Cf emits one neutron per second, it will take almost a million seconds (12 days) to get one count. In our example we need 73.7 counts/s, as calculated in the preceding section. One microgram of ^{252}Cf emits 2.34×10^6 neutrons/s. So the minimum mass of ^{252}Cf needed to get 1% relative precision in 1000 s can finally be calculated as follows:

$$(m_{Cf})(2.34 \times 10^6\ \text{n/s})(1.47 \times 10^{-6}\ \text{count/Cf n}) = 73.7\ \text{counts/s},$$
$$m_{Cf} = 21.4\ \mu\text{g}.$$

This is a modest amount of ^{252}Cf for a shuffler and is about all that was needed for the Billet Shuffler and the Liquid Raffinate Shuffler (for greatly different reasons). In this case, having 500 g of highly enriched uranium leads to a large fission probability (for shufflers).

4. The Initial ^{252}Cf Mass

If you fabricate a shuffler and put in the minimum ^{252}Cf mass, it will meet the specifications today, but not next year. In 147 days the neutron yield from the californium will be 90% of the original yield. In 2.65 years the yield is cut in half.

The initial ^{252}Cf mass must allow for the time span during which the specifications are to be met. Figure 20 shows the exponential decay of ^{252}Cf and other californium isotopes that are likely to be present. Shuffler sources are not used for more than a decade, so the other californium isotopes are not important. If our uranium sphere example specifies a useful life of 6 years, then the mass after 6 years of decay will be 21.4 µg and the initial mass at time zero is 103 µg.

If you are dissatisfied with this mass because it forces too large a shield, return to the beginning of the process and pick a larger new detection efficiency or a longer assay time. You cannot change the minimum number of delayed neutron counts unless you can change the background rate by adding more shielding or finding a new installation location.

Once you have an acceptable ^{252}Cf mass, think about all of the approximations you may have made to get to that point and decide if you want to apply a margin-of-error factor. Because the background rate may be higher than you estimated, and some of the materials you assumed to be near the assay chamber may get changed during mechanical design, you may want to double the initial ^{252}Cf mass you have calculated. If that requires too much shielding, you are ready for another iteration or set of compromises. If the calculations were carefully done with an accurate MCNP model and the actual design follows your MCNP design, the calculated ^{252}Cf mass is quite trustworthy.

To continue with the uranium sphere example, let us assume that the final ^{252}Cf mass is 150 µg instead of 103 µg because the assay chamber was crudely approximated and the actual detection efficiency was not accurately known. This is not a large mass as shufflers go, and whether we assume 100 or 150 µg will not have an important impact on the rest of the physics design. If we had calculated 500 µg, arbitrarily going up 50% to 750 µg would be very serious, and we would have to carefully reconsider and recalculate the initial mass.

If there are some key design features in your assay chamber that cannot be changed without affecting the fission probability or detection efficiency, it is important to ensure that they are present in the final mechanical drawings from which the fabrication will be done. A change in material from polyethylene to steel in the vicinity of the fissile material can make an important difference in the neutron flux inducing fissions.

When the ^{252}Cf is ordered from a supplier, the mass on a specific date should be requested even though it is not a certified value. Even better is to place an open order with the delivery date to be given later when the installation date of the shuffler is set. In any case, the supplier should take into account the decay of the source during preparation and shipping so that the ^{252}Cf arrives with the mass you wanted. The actual ^{252}Cf may differ from your specification as much as ±10% because of the difficulties in source preparation.

5. ^{252}Cf Shielding

Once a mass of ^{252}Cf is chosen, the overall dimensions of the new shuffler can be calculated. The storage block has one set of dimensions (if the source is not stored below the floor) and the assay chamber has another. The assay chamber must be large enough to hold the objects to be measured and have wall thickness to shield personnel from the ^{252}Cf radiations.

One microgram of ^{252}Cf produces a dose rate of 2.45 mrem/hr at one meter, if unshielded. Our 150-µg example would produce 368 mrem/hr at one meter, a rate that must be reduced to the facility's acceptable value with shielding. Assume that the facility wants no more than 0.5 mrem/hr in contact with the shuffler. Two decisions must be made: What material or materials will constitute the shields, and what are their thicknesses? The answers are different for the storage block and the assay chamber.

a. Storage Block

Until about 1990, the storage block design used in Los Alamos shufflers followed the scheme and calculations by H. E. Hootman of Savannah River.[11] The block had a small core of heavy metal (typically tungsten) to attenuate the gamma rays from ^{252}Cf. This was surrounded by a thick layer of polyethylene (or a similar moderator) to attenuate the neutrons. Finally, a thin outer layer of heavy metal (typically lead) attenuated the 2 MeV gamma rays following the capture of neutrons in hydrogen.

This outer layer of heavy metal was the main problem with the design. Even though it was thin (commonly half an inch), it was very heavy because it had a large surface area. Being thin, the attenuation it gave to 2 MeV gamma rays was not great. Making it thick enough to satisfactorily attenuate 2 MeV gamma rays would make its weight even more difficult to manage.

Nevertheless, satisfactory storage blocks were made because contact dose rates allowed in those days were usually 5 mrem/hr, not 0.5 mrem/hr, and the distance from the block to reasonable personnel locations gave even more attenuation.

Something better had always been desirable and when facility limits dropped to 0.5 mrem/hr, something better was almost mandatory. Hootman noted the positive effects of using borated materials to absorb neutrons, but the price of borated polyethylene limited its use. Two new designs were able to gain the benefits of using borated materials without the high price tag. With boron present, the neutron captures produce gamma rays with energies of about 0.4 MeV rather than 2 MeV, so the outside heavy metal layer can be omitted. The heaviness is gone and the shuffler's frame can be simplified.

One design with borated material, created with MCNP calculations, has layers of normal polyethylene separated by thin layers (0.25 in.) of borated polyethylene. Most of the neutron captures occur in the thin borated layers.

A second design, created by Frontier Technology of Xenia, Ohio, is a slurry mixture of a hydrogenous resin, polyethylene beads, and boric acid. In this design, the boron is uniformly distributed within a moderating medium—the ideal condition for absorbing neutrons. The slurry is poured into a mold, where it quickly hardens.

Tests have shown that these two shield designs are equivalent, at least on the scale needed for a 500 µg ^{252}Cf source (about 4 ft. on a side). Combining the measurements done by Frontier Technology with those done at Los Alamos provides data over a wide range of shield sizes. If you prefer a one-piece shield, or a few large pieces that can be assembled, the Frontier Technology process is more convenient. The slurry can be coaxed into oddly shaped molds and fills corners nicely; cutting and stacking oddly shaped pieces of polyethylene will be more expensive and won't shield any better, if as well. But, if you need to break a shield into pieces small enough to pass through a normal door, the layered approach is probably preferable.

For the 150 µg of ^{252}Cf example, what is the overall size of the shield that will give only 0.5 mrem/hr on contact? Our measured shielding data shows that we will have 0.5 mrem/hr on the surface of a 4-foot-wide shield if the ^{252}Cf mass is 43 µg. In other words, 150 µg behind 2 ft. of shielding will have a contact dose rate of 1.7 mrem/hr, not 0.5 mrem/hr. It is not clear how much larger the shield would have to be to meet the specifications because our data stops at a thickness of 26 inches and the neutron dose rate has begun to flatten out with thickness. But, we have a clear conflict between the shielding specification and practicalities.

One option is to increase the detection efficiency so that a smaller ^{252}Cf mass can be used. In this example, we could go from 20% to 60% in efficiency with known techniques and the necessary ^{252}Cf mass would drop from 150 µg to 50 µg. Because this is close to the desired value, perhaps the facility would note that 0.5 mrem/hr would be exceeded for only a short period in the source's life and set up a temporary small exclusion zone around the shuffler, which would reduce the dose rate to 0.5 mrem/hr.

But if that is true, we could retain the much cheaper 20% detection efficiency and 150 µg by creating a permanent exclusion zone about a foot wide. If the facility agrees to this logic, 150 µg could be used and the fabrication expense of an enhanced detection efficiency could be avoided.

But clearly, a compromise is necessary when it comes to a shielding problem such as this. A limit of 0.5 mrem/hr on contact is not a problem for shufflers with small ^{252}Cf sources (e.g., Billet and Liquid Raffinate shufflers), but is simply impractical for larger sources—unless you bring in a fresh concept.

Two shufflers have not even had storage blocks, even though their ^{252}Cf masses were about 250 µg. They were installed on floors resting on the ground so that it was possible to drill through the floor into the ground and store the ^{252}Cf sources in cylindrical shields made mostly of polyethylene. With a hole 4 to 6 feet deep, there was no difficulty meeting the facilities' shielding requirements. The background rate was also lower than usually found with a normal storage block. While this technique is less expensive and takes less space than a storage block, obviously not all installation sites can accommodate a hole through the floor.

Another approach is to seek new shielding materials. Various studies have been made and commercial fabricators will create many combinations of materials, but we have not used any of these shielding materials.

b. Assay Chamber Walls

A storage block that has a width of 4 ft. means that the source positioned in the block's center is surrounded by 2 ft. of shielding. The simplest approach to the thickness of the walls of the assay chamber might seem to be to use 2 ft. of the same shielding. But the detector tubes need to be in embedded in polyethylene that doesn't contain boron, and this polyethylene should extend behind the tubes for several inches. Furthermore, the storage block's small core of heavy metal is rarely used in the assay chamber, with the rare exception of taking shielding credit for the metals used in spectrum tailoring.

So we need to begin anew for the walls. The inner geometry of the assay chamber is fixed independently of the shielding. Figure 27 shows a cross section of the standard 55-gallon-drum shuffler that uses as much as 550 µg of ^{252}Cf. The assay chamber is hexagonal to approximate the circular shape of the drum. The guide tube for the ^{252}Cf source runs along a block of iron. The iron gives some shielding toward the rear (where personnel are unlikely to stand) but it will be ignored. It acts as a reflector to send 25% more neutrons toward the drum and does no important spectrum tailoring.

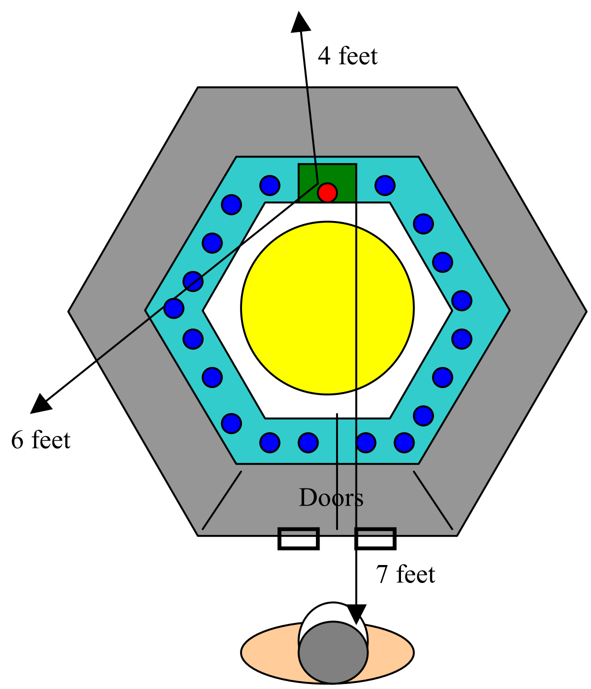


Fig. 27. A horizontal cross section of the standard shuffler for 55-gallon drums is shown with an operator positioned in front of the doors. A drum is surrounded by detector tubes embedded in polyethylene, which is wrapped with an outer layer of borated polyethylene and half an inch of lead to form the shielding. Distances to the ^{252}Cf source and the amounts of shielding in the different directions are shown.

Detector tubes are embedded in polyethylene and surround the drum; there are more above and below the drum. The shielding beyond the detector region is composed of alternating layers of polyethylene and borated polyethylene, however, it is only about 14 in. thick.

Additional factors compensate for the lack of a heavy metal inner core and relatively thin neutron shielding. A half-inch of lead is wrapped around the borated polyethylene to help with the gamma-ray attenuation. While the source is relatively far from people who might stand in front or to the side of the shuffler, the source is closer to them if they stand behind the shuffler. A physical barrier should be placed behind the shuffler to limit access unless additional shielding is added. People normally stand outside the doors, as shown in Fig. 27, to load and unload containers, but there is no reason for them to stand there during a measurement. Standing 7 ft. from the source reduces the dose rate by a factor of 5.4 even without any shielding, compared to the standard 1-m distance. (The $1/r^2$ law still works quite well, even with intervening shielding materials.)

The worst place to stand during an assay is at the rear of the shuffler. The distance to the source is only slightly more than the standard 1 m and the shielding is about 2 ft. thick. With the initial size ^{252}Cf source, the dose rate at the rear will exceed 5 mrem/hr when the source is in the irradiating position. This problem is mitigated by locating the shuffler near a wall (or in a corner), and leaving a space that is not attractive to room occupants. Then a radiological barrier can be placed at the rear to warn personnel. There is never any reason connected with the shuffler to go into this space at any time, let alone when a measurement is in progress. An alternative to this approach is to stack more shielding behind the shuffler or redesign the shuffler body with more shielding. In any case, the dose rate through the walls of the assay chamber can be managed several ways, so the facility preference for a physical or an administrative solution can be met.

Shufflers of other designs have met the specifications in other ways. The Billet Shuffler's specification was 0.5 mrem/hr in contact. With the largest ^{252}Cf source present, the measured dose rate was 0.6 mrem/hr. The specified dose rate is found only 2 in. away from contact and the facility simply made it an administrative rule to not sprawl on the shuffler. The Liquid Raffinate Shuffler met the dose rate requirements while it was stored in a concrete wall within a polyethylene and lead plug; for an irradiation, it moved into a hot cell with even more shielding, so the effective thickness of the assay chamber's wall was more than sufficient. The Spent Naval Fuel Shuffler was located in a hot cell and could take advantage of this additional shielding and the great distance between the shuffler and any personnel. Older shufflers that had to meet the more generous 5 mrem/hr limit had no problems. In fact, the background radiation where one of them was located was so high it was safer to hug the shuffler than stand away from it. The Pass-Through shufflers had extremely effective underground storage for their ^{252}Cf sources; the shufflers' walls were too thin to meet 0.5 mrem/hr in contact, so people were kept a short distance away during measurements by rope barriers.

6. Assay Chamber

The design of the assay chamber gets to the heart of a shuffler. The rest of the instrument supports the action within the assay chamber. The assay chamber generally has the first four components in the following list and may have any of the others. Figure 27 illustrates some of these components.

- An empty chamber to receive the object to be measured.
- One or more doors that provide access to the chamber.
- Neutron detector tubes and amplifiers surrounding the chamber.
- A guide tube for the ^{252}Cf source and its flexible cable.
- An optional thin layer of cadmium around the inside wall of the chamber.
- An optional metallic reflector behind the source to send more ^{252}Cf neutrons toward the object.
- An optional spectrum tailoring set of materials.
- An optional turntable to rotate the object during the measurement.

Some other items may be integrated into the assay chamber but are not really needed for the assay. And an occasional shuffler does not even have what normally is a necessary component.

Designing an empty chamber may sound simple, but there are criteria that must be met. If you make a chamber larger than the object to be measured, there will be gaps through which neutrons can pass without encountering the object. Some will scatter off the walls and return for another chance, but others will be lost in the walls and wasted. This forces the use of a larger ^{252}Cf source for a given performance specification of the shuffler. The standard shuffler for 55-gallon drums is also used for small (1/8 gallon) cans. The waste of neutrons is large, but the assay is still quite precise in just a few minutes. The alternative is to build a set of shufflers with different sizes of assay chambers. The expense is unnecessary and the floor space would rarely be available, so why not use a shuffler that is much bigger than the ideal size, as long it does the job? The assay chamber of the Billet and Uranium Scrap shufflers were built to closely match the size and shape of the billets and cans because they were to serve special purposes with well-defined containers. The liquid raffinate filled its assay chamber as it flowed in from the bottom and out the top.

Doors can swing open, roll to one side, be operated manually, or be motorized. Some shufflers don't even have doors. The Liquid Raffinate Shuffler didn't have a door because the assay chamber was essentially an expanded section of a hot cell's pipe through which the liquid flowed. The Spent Naval Fuel Shuffler also didn't have a door; a spent fuel assembly passed through a hole in the shuffler body while inside a hot cell.

Enough neutron detector tubes must surround the object to provide the required detection efficiency. An efficiency is easily measured with a tiny ^{252}Cf source in the center of the chamber, but the average energy of this energy spectrum is higher than that of delayed neutrons. For example, the standard 55-gallon-drum shuffler has a detection efficiency of 18% for ^{252}Cf neutrons and 24% for delayed neutrons. The detectors were deliberately optimized for delayed neutrons by embedding them at a certain depth inside a block of polyethylene. This depth can be fine-tuned if the material to be measured is known. A drum of paper already provides some moderation and the tubes' depth can be shortened. A drum of glove-box metal pieces is not a good moderator and the depth should be increased. If a wide variety of moderating and nonmoderating materials will be measured, a compromise depth can be selected. More information on the arrays of detectors is given in the next section.

Los Alamos shufflers have always used Reuter-Stokes' 1-in.-diameter ^{3}He tubes with a pressure of 4 atm. Tubes with 10 atm. are now available at reasonable prices, so they could be used to increase detection efficiency without adding new tubes. Various amplifiers based around the AmpTek A111 have been used. If the gamma-ray field in the assay chamber is high enough (> 1 R/hr) to create pulses in a tube, the number of amplifiers is increased, up to the point of one per tube. A convenient way to attach one amplifier to each tube is with the Precision Data Technology PDT-110A that screws onto a tube's base. This was done for the Dounreay leached hulls shuffler because fission products were still present (a thin layer of lead was also wrapped around each tube to help attenuate the gamma rays).

The guide for the ^{252}Cf source and its cable is a half-inch-diameter stainless-steel tube. There is enough space around the capsule to prevent binding, as long as any bends are sufficiently shallow. For the usual Model 100 capsule with the Los Alamos coupler that attaches the source to the cable, the radius of a bend cannot be less than 9 inches. Inside the assay chamber the tube is usually straight, but the tube in the Spent Naval Fuel Shuffler formed a circle around the spent fuel assembly. An unusually sharp bend was needed for the Liquid Raffinate Shuffler, so a thinner-walled guide tube was used along with a one-piece Model 100 capsule and coupler to reduce its overall length.

In most cases, the inside walls of the assay chamber are lined with cadmium 0.016 or 0.032 in. thick. This prevents the lowest-energy neutrons from leaving the polyethylene walls and re-entering the assay chamber. For all but the smallest particles of fissile material, these low-energy neutrons would badly distort the distributions of fissions within the material. Most of the fissions would occur on the outer surface and the count rate would be only a weak function of the mass of fissile material (see Appendix A). The Liquid Raffinate Shuffler was an exception because the uranium was in a solution that already was an excellent moderator. There was no way to prevent low-energy neutrons from inducing fissions, but it didn't matter in this case. The uranium was in a homogenous solution, so there were no problems with particle sizes and whatever nonuniformity there was in the distribution of delayed neutron precursors was always the same. Normally, low-energy neutrons are unwanted and nearly eliminated by the cadmium. For personnel health protection against the heavy metal, the cadmium is always attached to and covered by a thin sheet of stainless steel, making the cadmium inaccessible in routine work.

The ^{252}Cf in the Model 100 capsule is an isotropic source, so at least half the neutrons leave the source in the direction away from the object to be assayed. The fission rate in an object can be increased by about 25% by placing an iron reflector behind the source to scatter neutrons toward the assay chamber (Fig. 27). A thickness of about 4 in. is commonly used as a compromise between bulk, weight, and effectiveness. Some detector tubes are removed to make room for the reflector, so users should check that using a reflector gives a net gain in detection efficiency.

Spectrum-tailoring materials have been used to avoid making adjustments for fissions in ^{238}U, but this involves putting several inches of various metals between the source and the object of interest, reducing the neutron flux somewhat. The source's mass can be increased to compensate for the loss, along with a commensurate increase in shuffler size and cost. A decision must be made early in the design stage as to which unwanted feature has to be accepted.

A turntable is not always necessary. The Liquid Raffinate Shuffler dealt with a homogenous liquid and a ^{252}Cf source in its center, so the effect of a turntable was achieved without turning anything. The Spent Naval Fuel Shuffler spun the source around an assembly instead of spinning the assembly. But the standard 55-gallon-drum shuffler greatly benefits from a turntable. A distribution of delayed neutron precursors is needed that is proportional to the distribution of fissile material. If the ^{252}Cf source was simply held near the center of a stationary drum and then removed, the distribution would be inappropriate. A nearly correct distribution can be produced by rotating the drum and scanning the source vertically along the drum's side. The Uranium Scrap Shuffler also rotated the cans because the packing of the uranium metal pieces could be irregular; irradiating from only one side would not ensure uniformity.

7. Detector Tube Arrays

Detector tubes are usually embedded in banks of rectangular or semicircular pieces of polyethylene. A cross section of a rectangular bank is shown in Fig. 28. Holes are drilled into the polyethylene at the tube position. A semicircular bank would have the same parameters.

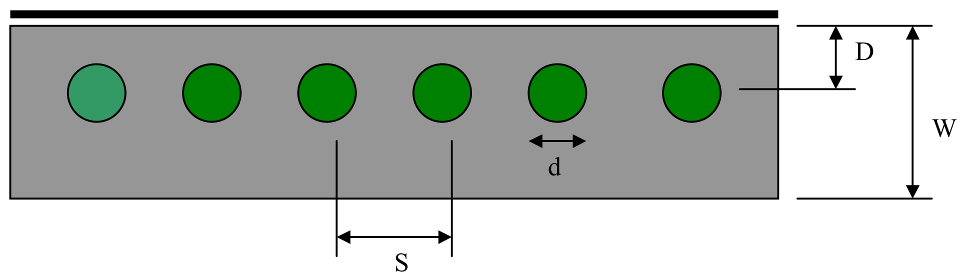


Fig. 28. A detector bank consists of ^{3}He tubes embedded in polyethylene. The heavy line at the top is an optional layer of cadmium and stainless steel lining the assay chamber. The assay chamber is located above the cadmium and steel liner. The important geometric parameters are indicated.

The width *W* of the bank is often 4 in. because it works well and is a standard size for polyethylene. The tube diameter *d* is typically 1 in., so the holes for the tubes are drilled slightly larger (e.g., 1.125 in.). The depth *D* between the tubes' centers and the side of the bank facing the fissile material affects the detection efficiency as a function of neutron energy, and the spacing *S* between tubes affects the detection efficiency for a given depth. For delayed neutrons, the depth *D* is smaller than the depth used in passive neutron counters for spontaneous fission neutrons. A general-purpose depth for shufflers is 1.5 in. A spacing *S* less than 2 in. is counterproductive because a tube absorbs low-energy neutrons from its immediate vicinity and the tubes compete for these neutrons when the they are too close together. They can be spaced as far apart as desired if the detection efficiency needed is still met. Monte Carlo calculations are useful in designing the array of tubes needed to meet the shuffler's specifications

If your design has tubes as closely spaced as possible to get the maximum detection efficiency, but this is still not good enough, a second row of tubes can be added. But Monte Carlo calculations should be done to optimize this case because *D* for the first row of tubes will probably shrink from the 1.5 in. suggested above. A multirow design has never been needed in Los Alamos shuffler.

The dimensions of the polyethylene not shown in Fig. 28 are dictated by the overall shuffler design. The bank can expand and shrink to include different numbers and lengths of tubes.

An alternative to drilling long holes in polyethylene blocks is to make a "sandwich" of tubes between slabs of polyethylene. Filling part of the gaps between tubes is usually beneficial, but this design should be calculated carefully to optimize the detection efficiency.

The heavy line shown at the top of Fig. 28 represents other materials that may be attached to the bank. Typically there is a cadmium sheet in contact with the polyethylene, covered by a sheet of stainless steel. There could also be a layer of lead or tungsten to attenuate intense gamma rays.

The electronics associated with the tubes in a bank will be discussed in a later section. But in general terms, the tubes need a high-voltage supply (≈ 1680 V) and the amplifiers need a low-voltage supply (5 V) to produce TTL signals for the 12-channel scaler. If all the signals are combined internally, as is usually done, each bank will have 3 electrical cables.

8. ^{252}Cf Motion Requirements

Delayed neutrons are produced during the irradiation, but cannot be counted against the background from the ^{252}Cf source. During the irradiation, their emission rate grows because many precursors have lifetimes longer than the irradiation time. When the irradiation ends, the emission rate of delayed neutrons begins to diminish rapidly. After an 11-s irradiation of ^{235}U, most of the delayed neutrons are released in the next 20 s. Obviously, you will count a larger fraction of these delayed neutrons if the ^{252}Cf source is removed quickly. This defines the most important feature of whatever is to move the source within the shuffler. It is less crucial to move the source into the irradiation position quickly, but a rapid motion here makes the mathematical expressions of a shuffler's activities more accurate.

How quickly should the source move from the assay chamber back to the storage block? Some early Los Alamos shufflers used stepping motors tuned to run as fast as possible, and these sources moved about 5 ft. in about 0.33 s. But the tuning process was time-consuming and unique for a given set of equipment, and aging effects would require periodic retuning. It was decided to give up 10% of the delayed neutrons and use a slower, but very reliable, stepping (or servo) motor system from Compumotor that needs no maintenance. A move of 5 ft. is now generally done in about 0.75 s. To make up for the 10% drop in counts, the mass of the ^{252}Cf source can be increased by 10% or the assay time can be increased by about 10%. This sacrifice is well worth the elimination of the maintenance problems.

Early European shufflers used pneumatic systems that were quick but could not be used to slowly scan along a container. Modern shufflers use a stepping motor to drive a cable attached to the source. The shuffler at Cadarache required a fast motion over a long distance, so a large motor with a high speed (up to 7 m/s) and high torque was adapted for use there.

Stepping motors are very precise and accurate in their rotations. If you want the source to move exactly 5 ft., the largest error in the final position will not come from the motor. If one inch of linear motion corresponds to 625 motor steps, then the motor is told to take 37,500 steps. The motors have been extremely reliable in taking such a number of steps, but in case there is a slight malfunction the motor indexer can sense the problem and quickly make up the error with some extra steps. In such a case, the shuffler's computer is informed of the problem and the assay might be considered suspect. In practice, such an error has never been experienced. More common is a total interruption of the motion because the requested velocity was too high for the torque of the motor. By staying within the velocity and acceleration limits of the motor, the correct number of steps will be taken. Each step typically gives 0.0016 in. of linear travel, but the cable usually snakes its way through the larger guide tube and will not come to rest with a reproducibility as good as 0.001 in. But a difference in position by even 0.1 in. would be unimportant and this probably overestimates the error in replicated motions. The shufflers most sensitive to the ^{252}Cf position have the source close to the container; these include the Scrap Shuffler, the Product Oxide Shufflers, and the Dounreay leached hulls shuffler. None has had any problem reproducing measurements because of the tiny ^{252}Cf position variations.

C. Detailed Designs and Fabrication

The physics design sets the principal parameters that are needed to meet the measurement goals. Practical issues may force some changes and these should be carefully considered. But the mechanical, electrical, and software personnel can now proceed toward design drawings and other documents from which fabrications will be done.

1. Mechanical

The mechanical designer should retain (as much as possible) the physics design and add the many details that lead to a practical shuffler. How the door or doors operate is usually independent of the physics and depends on the facility. There are many questions to be addressed. How will the shuffler be installed in the facility? Is there head room for a hoist, if needed? What is the size of the smallest entry into the location for assembly? How are the electrical cables routed through the massive shielding? What turntable will hold the maximum load? What earthquake resistant features are needed? And so on.

The final product is a set of drawings that shows every piece to be fabricated and how they fit together. The drawing package includes a parts list from which orders are placed. Some of the items (e.g., ^{3}He tubes) should be ordered well before the drawings are finished because it can take months to procure them.

2. Electrical

The electrical design is not independent of the mechanical design. Both designers must know the number and sizes of tubes and cables, for example. Space for amplifiers in the vicinity of the detectors must be agreed on by both parties.

But much of the electrical design deals with modules in an electronics rack and has no impact on the mechanical design. Off-the-shelf items can be specified and ordered a few weeks before they are needed. But shufflers usually have some custom modules that must be designed and even built in-house. The status panel showing the states of the proximity switches can vary radically among shufflers, although the underlying electronics may be the same. Custom controllers for analog turntable motors have been designed and built in-house.

The assembly and testing of the junction boxes for the ^{3}He tubes and amplifiers are crucial activities that deserve careful attention. Finding problems at this stage is much better than discovering them after the shuffler has been assembled.

The electrical design must coordinate with the software design. For example, agreement is needed on the assignment of bits on the input and output parallel ports dealing with signals. The hardware to be used as peripherals to the computer should be agreed to as early as possible.

3. Electromechanical ^{252}Cf Motion Control

The mechanical and electrical designers need to be involved in selecting the electromechanical system that moves the ^{252}Cf source. The turntable design is another area where interests overlap. The stepping motor system has been described already. The other components of the motion subsystem are described here.

The cable used to move the source through the assay chamber is made by Teleflex. The cable has an inner core of several steel wires in parallel; this is tightly wrapped by another steel wire, which itself is wrapped by a second steel wire. This type of cable was originally intended to control rudders and ailerons of airplanes and ships., so there is no question about its strength being adequate for shuffler use. The outer wire wrap is rather coarse and Teleflex makes gears that mesh nicely with it. Using Teleflex gears, Los Alamos designed a gearbox to drive the cable with the stepping motor. Aluminum gears were found to wear excessively, but steel gears have proven durable.

A Model 100 steel capsule containing the ^{252}Cf source has a threaded end to which a Los Alamos-designed coupler is screwed. The other end of the coupler screws onto the Teleflex cable. All of these threads and the threads of four set screws are cemented with LokTite. A source attached in this manner has never come loose accidentally. Heat will loosen the cement if it necessary to separate the source from the cable. The ^{252}Cf suppliers (Frontier Technology and the DOE Isotope Products Office at Oak Ridge) have supplied shuffler sources already attached to cables in this manner.

4. Software

A standard code to operate shufflers has been developed at Los Alamos, but it requires customizing for a specific shuffler or facility. The important algorithm that controls the measurement process and calculates the assay result does not change. Peripheral matters that may change are the contents of printouts, the levels of password-protected options, and the choices for defaults of some options.

Table VIII is a generic list of shuffler menu choices and the password level (operator, supervisor, manager) that is often assigned. A supervisor can also do the operator's options. A manager can do all options. The password level required for an option can be customized to a facility's needs.

Table VIII
Generic Shuffler Menu Options

Menu Option	Description	Lowest Password Level
File		
Edit Access List	The authorized users, their passwords, and their password levels are created, edited, and deleted only by those with the highest authority.	Manager
Print Current Window	The contents of the selected window are sent to the printer.	Operator
Archive	The results of previous measurements can be reviewed. The results can be selected by date and time.	Operator
Exit	This terminates the program.	Operator
Measurements		Operator
Assay	This is the normal measurement of fissile mass.	Operator
Bias and Precision	A preset number of replicated measurements are done on a standard to check the accuracy (measure the bias) and precision against accepted values.	Operator
Precision	A preset number of replicated measurements are done on some material (not necessarily a standard) to determine the precision.	Operator
Standard Check	An assay is done on an empty assay chamber to check for holdup and a second assay is done on a measurement-control standard.	Operator
Acquire Calibration Data	A calibration standard is measured; the data analysis ends with the measured count rate and its uncertainty. A set of such results can be used to form a calibration curve.	Operator

Menu Option	Description	Lowest Password Level
Safety Check	The proximity switches and status lamps are exercised and checked with the user's interaction.	Operator
Privileged		Supervisor
General Parameters	These parameters apply to all measurements.	Supervisor
Nuclear	Precursor yields and half-lives are given for the six groups of delayed neutrons (usually for ^{235}U). The half-life of ^{252}Cf is given along with the reference date for decay corrections	Supervisor
Archiving	The maximum number of measurements to be archived is specified.	Supervisor
Item Type Names	Facility-specific names for types of items to be assayed are given.	Supervisor
Bias and Precision	The number of repeated measurements and the expected results are specified for some standard item.	Supervisor
Test Position	The motion of the ^{252}Cf source and the expected count rate are specified.	Supervisor
Standard Check	The frequency of this check and whether it is even required is given. The expected results are also given.	Supervisor
Compumotor I/O Bits	The significance of each bit on the parallel ports of the Compumotor Indexer is defined.	Supervisor
List All Parameters	All of the general parameters can be viewed or printed.	Supervisor
Item Parameters	These parameters apply to individual item types.	Supervisor
Assay	The sequence of ^{252}Cf motions is defined. The background count time and delayed neutron count time are specified. The uses of a turntable and flux monitors are set.	Supervisor
Assay Diagnostics	Pairs of detector banks to be compared are set. The maximum allowable deviation of the cycle correction factor from unit is selected.	Supervisor
Normalization	A normalization factor *may* be applied if there is good reason to do so. However, this is rarely different from unity.	Supervisor
Calibration	The calibration parameters for each item type are specified here.	Supervisor
Bias Correction	A bias correction *may* be applied, if there is good reason to do so. However, this is rarely different from unity.	Supervisor
List All Parameters	All of the item parameters can be viewed or printed.	Supervisor
Diagnostics	These simple operations help test the equipment and locate problems.	Supervisor
Store Cf Source	The ^{252}Cf source is quickly returned to the store position. This is the same routine used to store the source if the door is opened at the wrong time.	Supervisor
Move Cf Source	The ^{252}Cf source can be moved any number of motor steps in either direction, with the specified speed and acceleration.	Supervisor
Count with No Cf Motion	The 12-channel scaler counts for the specified time and displays the results for each channel along with their sum and rate.	Supervisor
Move Cf to Test Position	The standard position is defined in the general parameters. This option moves the Cf source to that position.	
Short Printout	The normal short printout is selected for later use.	Supervisor
Medium Printout	In addition to the information on a short printout, a two-page printout showing intermediate calculations is selected for later use.	Supervisor
Long Printout	In addition to the information on a medium printout, a multipage printout showing all data for all shuffles is selected for later use.	Supervisor
Print Last Results	The data from the last measurement that is still in the program's memory is used for a new calculation and a new printout. New calibration parameters may be used and more information can be printed than in the first analysis. Any of the short or long printouts can be selected before printing.	Supervisor
Watch Parallel Bits	The input bits can be examined as the proximity switches are exercised.	Supervisor
Set Parallel Bits	The output bits can be set to exercise status lamps and an analog turntable.	Supervisor
Test Door Proximity Switch	This is a portion of the Safety Check.	Supervisor
Test Cf Proximity Switches	This is a portion of the Safety Check. (The Cf source will be moved.)	
Test Status Lamps	This is a portion of the Safety Check.	Supervisor
Test Rotation Motor	The turntable can be started and stopped.	Supervisor
Write ASCII Data	An ASCII file containing the raw data from a measurement will be written. In the newest software, this option is not in the Diagnostics menu; it is part of the measurement window.	Supervisor
Load Indexer Program	This downloads the program for the Compumotor Indexer from the shuffler's computer.	Supervisor
Windows	The windows in the display may be arranged in various standard Microsoft Windows ways.	Operator
Help	This currently only gives information about the program. It may give actual help some day.	Operator

Some parameters unique to shuffler design and installation are placed in a so-called configuration file that is read by the shuffler's software at startup. Some lines of the file are simply identifying statements that have no effect on the shuffler's operation, but only appear on headers of printouts. Other lines should not be changed unless there has first been a hardware change: the number of stepping motor steps that give one inch of linear travel, the type of turntable rotation motor, or a time delay to be used on the turntable's analog motor to stop it in the proper orientation.

D. Installation Issues

1. Temperature and Humidity

A shuffler's electronics has the usual requirements common to off-the-shelf electronics. Ambient temperatures should be less than 90˚F (32˚C) and there should be no condensing moisture. Much of today's electronics, including the Compumotor Indexer, are rated for 122˚F (50˚C), but the temperature must be as low as the most sensitive component. If the ambient temperature is too high for the electronics, an air-conditioned electronics rack can be used.

Condensing moisture is clearly a problem for electronics and must be avoided. A dehumidifier would mitigate the problem, but none has ever been needed. An air conditioner, if used, also removes moisture from the air.

High humidity, even if noncondensing, is a better conductor of electricity than dry air. The only place this matters to a shuffler is inside a junction box where high voltage is applied to the ^{3}He tubes. Arcing from the high voltage wires to the walls of a box can occur if the gap is short and the humidity is high. The assembly of the box must keep the wires short and as far from the walls as possible. The box itself is usually made from two pieces of aluminum; the larger piece is machined from a solid block and the smaller piece is a plate used as the lid. The lid is sealed to the body of the box with a greased O-ring in a groove. Moisture will slowly leak into the box through the connectors, so desiccant capsules are built into the lid to absorb the unwanted moisture. These capsules screw into holes in the lid, again using O-ring seals, and can be easily replaced. In a dry climate like Los Alamos, humidity is never a problem and these measures are not necessary. In the wettest climates these measures have been effective and the desiccants are rarely replaced. The O-ring seal of the Billet Shuffler at Savannah River slipped while the lid was first attached and within a summer's week we could see arcing (very high, erratic background count rates); reattaching the lid properly eliminated the problem.

2. Interference with Neighboring Instruments

Standalone shufflers have a lot of neutron and gamma-ray shielding, and dose rates meet facility limits. But other instruments can be much more sensitive to radiations than humans and the small leakage through the shielding may be detectable. Furthermore, radiations from nearby objects may interfere with the shuffler.

A shuffler has shared a small room with a segmented-gamma scanner (SGS) placed only about 10 feet away. They performed measurements at the same time without any problem because of the following conditions:

- The gamma-ray detector faced away from the shuffler. No gamma rays from the ^{252}Cf source were seen even in a background spectra.
- They were both measuring kilogram quantities of fissile materials, so the signals were strong.
- No fissile material was moved into or from either instrument while the other was counting. In other words, the backgrounds from the materials being measured were kept constant.

Gamma-ray spectrometers near shufflers at other facilities have never detected interfering gamma rays, so that potential problem seems not to exist. However, portal monitors use huge plastic scintillators that are extremely sensitive, so they can pick up small fissile materials passing through them quickly. One shuffler installation was 40 ft. from a portal monitor with no effective shielding between them. The background rate of the portal monitor was noticeably raised when the 500-µg ^{252}Cf source was in use outside the storage block. This led to more false alarms and less sensitivity. To lower the background rate, an iron plate was set against the shuffler body to attenuate the gamma rays.

At another installation, a shuffler with a 500-µg ^{252}Cf source was only about 15 ft. from a portal monitor, but there was no problem at all. To get to the monitor, gamma rays had to pass through a concrete wall on a diagonal. The attenuation was more than enough to prevent any interference.

Shuffler software assumes that the background rate is constant during the measurements. A new background is taken at the start of every measurement, but in most cases the background rate is quite steady. At one facility, however, plutonium materials were often on the move and the background was highly variable. Administrative controls of the movements were impractical, so additional shielding in the form of four inches of polyethylene was put along one side of the shuffler and background-rate variations became acceptable.

It is not likely that another instrument near the shuffler will produce neutrons of any importance. The AmLi sources in an AWCC are rather weak and would not be significant. No instrument with a D-T generator has been used near a shuffler and this is unlikely to occur. But moving large masses of plutonium in and out of a nearby instrument could change the background rate, as mentioned earlier.

Aside from the single portal monitor case, a shuffler has not directly interfered with or been directly interfered with by another instrument. The few cases of interference have always been caused by the radiations from materials put into the shuffler or the other instrument (or from materials being moved between instruments).

3. ^{252}Cf Storage Options

The facility can select one of various storage options for the ^{252}Cf source. Usually a shuffler is a standalone instrument that can even be moved to another location. In this case, there is a storage block adjacent to the assay chamber (above or to one side). The Billet Shuffler could be moved to another building because it had this design. These storage blocks have been as large as 4x4x4 ft, weighing about 4000 lbs.

An option that has been used three times at Savannah River is to store the source in the ground below the assay chamber; no block is used at all. The hole is about 1 ft. in diameter and 4 to 6 ft. deep. It is filled with a cylinder of polyethylene that has a small hole drilled through its axis for the guide tube of the ^{252}Cf source. Any gap is filled with polyethylene beads to prevent streaming. The savings in cost, size, and weight of the shuffler are big. Obviously, the shuffler must be installed on a ground-level floor and studies must be done to check that the hole in the floor will not cause a structural problem.

Other options have used unique features of the facilities. Three installations have used thick walls of hot cells as the storage locations. Twice an existing access port was used; the third time a new hole was drilled through the concrete. A polyethylene and lead plug filled the access port and the ^{252}Cf source was stored inside the plug. Leakage from the hot cell was prevented by sealing the plug in the port and by the negative pressure inside the hot cell.

4. ^{252}Cf Source Loading and Unloading

Loading and unloading ^{252}Cf sources takes only seconds—after days of administrative preparation. It is almost inevitable that the source has to be unshielded for a few seconds, hence the paperwork. Here is an outline of the process:

- Order a new ^{252}Cf source, schedule its delivery, and schedule the return of the old source for credit.
- Get the administrative permits to swap sources.
- Practice the operations with a dummy source on a cable.
- Assemble the people needed to do the job.
- Remove the old source and quickly place it inside a shield. (A cask supplied by Frontier Technology is rated for two sources and the old source can go into the empty slot.)
- Install the new source.
- Return the shipping cask with the old source.

The source-handling technique employed depends on the shuffler's design. Some break in the guide tube must always be made, but this usually means just undoing a couple of Swagelok connectors and possibly swinging the stepping motor and gearbox out of the way. Some specific examples are given below.

Handling a source for the standard 55-gallon-drum shuffler involves a 9-ft. section of small-diameter tubing through which the Teleflex cable can pass but through which the larger ^{252}Cf capsule cannot. The free end of the cable is slid through the tube until the free end sticks out a few inches; the source is still well shielded by the storage block. A quick pull on the cable's free end brings the capsule out of the block; the tube is swung to the shipping cask, and the capsule pushed into this shield by pushing on the free end of the cable. This takes about 10 s and the person holding the tube is always at least 8 ft. from the source. The process is reversed to install the new source. Practicing the moves with a dummy source on a cable minimizes the time. The Pass-Through shufflers use essentially the same technique.

With the Billet Shuffler, a plug was unscrewed from the front of the horizontal spike at the front of the assay chamber, exposing the tip of the guide tube. The handling tube described in the preceding paragraph would not work here because the ^{252}Cf source capsule comes out first, pushed from the rear by turning the gearbox by hand. A small crank handle was built into the gearbox to make this easy to do quickly. The capsule was guided into a shielded cask near the assay chamber. At first, a flexible tube was connected to the shuffler and the cask, but the additional friction slowed the transfer time, so a human handler stood behind the 2-ft.-thick door of the assay chamber and guided the capsule into the cask with a long pair of tongs. Most of the person was shielded, and the dose to the unshielded portion of the person's body was small (a few millirems) because the exposure time was short. Inserting a new source used these steps in reverse.

The Spent Naval Fuel and the Dounreay shufflers each used sources with 3000 µg of ^{252}Cf. A shipping cask was designed not only to provide the shielding but also to assist in the installation. A steel tube was connected between the cask and the shuffler's guide tube. A crank built into the cask pushed a new source into the shuffler or pulled an old source into the cask. The person turning the crank was safely behind the shielding of the cask.

For a new shuffler, or an old shuffler in a new facility, these operations should be carefully considered early in the planning and a practical technique agreed to before fabrication and installation.

5. Miscellaneous Installation Issues

Some installation issues are more facility-specific than others.

Earthquake regulations for a proposed site may require some additional structural stiffening. Cross members have been added to the storage block and extra bolts put into the floor. An analysis was done for the Liquid Raffinate Shuffler mounted on a hot cell wall; it was found to meet earthquake requirements without any redesign.

The 1-ft.-deep pit with the 55-gallon-drum shuffler can trap free liquids from some spill. If the liquids might contain dissolved fissile materials and a criticality accident can be imagined, the space in the pit can be filled with blocks of polyethylene or any other suitable material to limit the volume into which a liquid might flow.

Uninterruptible power supplies (UPS) may be used to keep the shuffler operating during a facility power failure. By using a UPS, an assay in progress can be completed and the ^{252}Cf source securely returned to the storage block. Without the UPS, the source may stop within the assay chamber if an assay is in progress. As long as the doors are kept closed, the source is still well shielded, but if someone opens the door, the source cannot be retracted and an alarm can't be given without power. It seems incredible that someone would open the doors of a shuffler while the power was off, but operators should be trained to keep the doors shut in any unusual circumstances. Once the power is restored, the Compumotor Indexer will automatically run its internal program in just a few seconds, detect that the source is not stored, and quickly return it to the storage block. All this happens long before the computer has even booted back up. The advantage of having a UPS is that the source will be stored at the end of the assay and the shuffler will remain idle until an operator begins another assay, presumably after full power is restored.

IV. OPERATING PROCEDURES

A. Startup Checkout

A newly assembled shuffler, or one that hasn't been run for a long time, should be tested in stages rather than expecting it to immediately make measurements. Individual components should be tested individually and then in simple combinations to make sure that they operate and interact properly. Only then should the normal measurements with long, high-speed motions of the source capsule begin.

Table IX gives a generic checkout procedure. Some of the details will vary among different shufflers. Many of these steps can be done with only a Teleflex cable without a source, or with a dummy ^{252}Cf source capsule on the cable. For a new shuffler, the ^{252}Cf source should be left out until these checks are passed.

TABLE IX
Generic Shuffler Checkout Procedure

Step	Description	Watch out for…
Load Indexer Code	Use the main shuffler software to download the Indexer's code into the Indexer. (See "Diagnostics" in the software description.)	There are no hazards here, but without the program, the Indexer will not process commands from the shuffler's computer.
Check Input Bits	Use the software "Diagnostic" option "Watch Parallel" to see if signals from the proximity switches are being received. The corresponding status lamps should also function correctly. Exercise the switches by opening and closing the door(s), rotating the turntable, and moving the ^{252}Cf source by rotating the stepping motor's shaft by hand.	If any proximity switch is not working properly, go no further until this is fixed. The shuffler's software will not perform a measurement if it finds incorrect signals, and the source should not be moved by the motor without all protective measures operating.
Check Status Lamps	A similar check on a higher level is done with the "Diagnostics/Check Status Lamps" option in the software.	This should not fail if the previous test was passed.
Check Output Bits	The shuffler's computer sets several bits on the parallel output of the Indexer. These bits control status lamps, the analog rotation motor (if there is one), and an audible alarm (if there is one).	Each bit can be turned on and off individually. Note the corresponding action. If there is problem, go no further until this is fixed. The status lamps are important sources of information for operational and safety reasons.
Auto ^{252}Cf Store	Move the cable a short distance (a couple of inches) off the store proximity switch and open the door(s) a crack. The cable should have automatically returned to the store position if the program in the Indexer is running. Repeat the test for a much longer distance (a couple of feet).	There is no hazard in doing this test, even with ^{252}Cf attached to the cable, but it can also be done without a capsule on the cable. This auto store must be working properly before the shuffler is put into service, for operator safety reasons.
Easy ^{252}Cf Store	Exercise the "Diagnostics/Store Cf" option after moving the source some distance off the store proximity sensor.	This should work without fail because of the earlier tests with the switch, Auto ^{252}Cf Store, and the stepping motor. This is a convenient way to quickly store the source from any starting position and it should be tested.
Stepping Motor Operation	The motor can be moved a short distance, slowly, using the "Diagnostics/Move Cf" software option. (1) With the door opened a crack, the move should not take place. (2) With the door closed, move a few inches (625 steps per inch) at a slow speed (10,000 motor steps/s). (3) Repeat the move with a negative distance to return the cable to the original position. (4) Move the cable a longer distance (tens of inches) with a slow speed, then with a higher speed (100,000 steps/s) and acceleration (100,000 steps/s^2).	If there is no Cf source on the cable, there can be no radiation hazard in case of a malfunction. If there is a malfunction and Cf source is attached to the cable, keep the doors closed, remove power to the motor, and return the Cf source to the store position by turning the motor's shaft by hand. Then fix the problem with the motor system. Go no further until this problem is fixed.
Programmed Safety Check	The shuffler software has the "Safety Check" menu option. Exercise it to verify that it works correctly.	If the previous checks were passed, this should not fail.
Check Detector Banks	(1) With no neutron source in the assay chamber, use the "Diagnostics/Count with No Cf Motion" option to check the background rate. Flux monitors will show no counts because they are very inefficient. (2) Take another count with a neutron source in the assay chamber. A weak ^{252}Cf source or an AmLi source emitting about 10^4 n/s is adequate. Use the "Diagnostics/Count with No Cf Motion" option again. If you must use the large ^{252}Cf shuffler source, move it close to, but not into, the assay chamber to avoid saturating the electronics. (3) After quick checks, perform long-term counts to discover any electrical noise or instabilities.	Similar detector banks should give similar count rates. Background rates should be consistent with the shuffler design and location; banks closer to the stored ^{252}Cf source will have higher background rates.

Step	Description	Watch out for…
Test Turntable Motor	Assuming the shuffler has a turntable motor, it can be either analog or a stepping motor. (1) An analog motor can be exercised through the computer with “Diagnostics/Test Rotation Motor” or with a “jog” switch on the controller in the electronics rack. The “jog” switch does not involve the computer or any cables, so it directly exercises the motor driver and motor. (2) A stepping motor can be exercised through the computer with “Diagnostics/Test Rotation Motor.”	There is no safety issue here, but many assays need the motor to be working. The software checks that the motor is working before and during assays, aborting a measurement if the motor is not turning. Using the motor during an assay is a software option set by the supervisor.
Maximum Source Speed and Acceleration	There is an upper limit to the speed and acceleration with which the ^{252}Cf capsule and cable can be driven without stalling the stepping motor. To find these limits, the cable should have a real or dummy capsule attached. (1) Determine the distance the source is to be routinely moved at high speed. (2) Use the “Diagnostics/Move Cf” option to move the source from the store position and back. (3) Use the same value for the speed and acceleration. Keep increasing them until the motor stalls in one direction or the other. (4) Remove power from the motor driver (not the Indexer) for a few seconds to reset it. Restore power. (5) Use “Diagnostics/Store Cf” to store the Cf source. (6) Reduce the acceleration and speed enough to ensure stall-free operation. This might be about 80% or 90% of the values that create stalls. (7) Long, high-speed moves (e.g., 90 in.) are done in under 0.8 s reliably with the 55-gallon-drum shuffler. If times must be much longer, a motor with more torque should be considered.	The key word here is “reliable.” It is not necessary to try to squeeze the last 0.01 s out of these times. A comfortable time will allow a good fraction of the delayed neutrons to be counted and the hardware will not be unduly stressed.
Simulated Assay	With or without a ^{252}Cf source attached to the cable, the motions of an assay can be exercised. Do a lot of these simulations to ensure that the speeds do not stall the motor. Examine the full printouts to see the times used in each stage; what are their averages and standard deviations? The latter should be very small (well under 1%). Use the average times in the “Item Parameters/Assay Parameters” window for the nominal values.	If the times are very irregular, investigate and fix the cause. Otherwise, the irregularities will limit the precision of the counts.
Precision Check	With the ^{252}Cf source installed and a standard material in the assay chamber, perform repeated assays with the “Measurements/Calibration Data” option. These data may not be actual calibration data; this option is merely a convenient way to make repeated measurements of count rates. The option “Measurements/Precision Check” should be used if calibration parameters have been established.	Compare the precisions shown on printouts for individual assays to the precision (standard deviation) of the set of results. They should be similar. If the standard deviation is much larger than the individual values, there may be an unwanted source of variation (e.g., irregular times).

Note that this is a deliberate, graded process. The tests start with static checks, then short and slow checks, and finally long and high speed operations. It is difficult to damage the shuffler equipment, if properly assembled, but it is still prudent to do the checks first without the ^{252}Cf source attached. The capsule is in no danger of being damaged by anything the shuffler might do, including a high-speed smash into the immovable floor of the assay chamber. If this were to be done the forward-overtravel proximity switch would turn power off to the stepping motor but not in time to prevent the collision. If the switch were to fail, the stall-detect feature of the motor would shut it down also. But it is easy to avoid this annoying event by starting slowly and working your way up to the high-speed moves.

B. Status and Scaler Lamps

The status and scaler lamps have both routine and special uses to diagnose problems. The store lamp and the lamps of the 12-channel scaler directly impact safety. The store lamp shows whether or not the free end of the cable is on the store proximity switch. Given the reliability of the ^{252}Cf source connection to the cable, it is inferred that the cable is in the center of the storage block when the lamp is on. But the lamps of the 12-channel scale are the ultimate indication that the source is not in the assay chamber. If they are lit brightly and steadily, the doors should not be opened because either the source is in the assay chamber or there is an electrical malfunction. If these lamps are flickering at the usual background rate, the source cannot be present and the doors may be opened safely.

Users should be trained to check these lamps before opening the shuffler doors. Lamps that repeat the signals on the electronics rack have sometimes been placed very near the doors. To my knowledge, there has never been an accidental exposure with this electromechanical system in operation, a ^{252}Cf source capsule has never come off a cable, and the interlocking between the proximity switches with the Indexer and computer system has not failed.

C. Periodic Safety Checks

The software has a periodic safety check option and facility operators can decide how often to apply it. It takes only a minute or two to run. The failure rate of the electronics has proven to be very low (one status lamp has burned out). The most important status lamp is the store lamp, which is fail-safe in the sense that if it is burned out it will be dark and that indicates that the source is *not* stored. Furthermore, the software will not even perform an assay if the store switch does not operate. The check can be done routinely with no impact on throughput.

D. Measurement Control

1. Regulated Measurement Control

DOE regulations require a measurement control plan for an assay instrument. Periodic measurements on standards must be performed to check that the instrument is working properly. Each facility determines an appropriate plan, so only the basics will be discussed here.

The standards chosen for measurement control checks might be calibration standards, but need not be. If oxide powders are chosen, the density of a powder is likely to change with handling and even without handling (thanks to gravity's relentless effort). Take measurements after shaking the can to loosen the powder and after tapping the can on a table top to settle the powder; the results may vary by 7% or more simply from a change of density that affects self-shielding. Using a powder for measurement control (or calibration) should include a handling procedure to ensure about the same density for all measurements. With this understood, powders have been used very successfully for measurement control purposes.

Two measurement options are built into the software to help with the measurement control data collection. The "Precision Check" option does a number (set by the user) of repeated assays and gives the average and standard deviation. The number is specified in the "General Parameters" option.

The user can perform the "Bias/Precision Check" option on a standard whose mass is known. Set the correct answer in the "General Parameters" option along with the number of repeated assays. The software completes the measurements, compares the average with the declared mass, and compares the standard deviation with the declared standard deviation.

In both types of repeated measurements, the user specifies a delay time between assays in the "General Parameters" window. This delay ensures that precursors of delayed neutrons decay before the next assay is started. If this is not done, the background rate for the next assay will be too high and the assay result will be low. Waiting 4 min. is an adequate time.

2. Internal Measurement Controls

The shuffler performs other measurement controls as part of every assay. These are not reported unless there is a failure.

- If a delayed-neutron channel of the 12-channel scaler reports zero counts, a problem is assumed to have occurred and the measurement is aborted with a message to the user. This is applied to background counts as well as counts after irradiations.

- The counts in pairs of detector banks should often have fixed ratios, within the limits of statistical fluctuations. The pairs to be compared can be assigned and their expected ratio given in the "General Parameters" option. The limits of the ratios may have to be expanded if fissile material scattered throughout 55-gallon drums is being measured, especially if the rotation motor is not used. This check is disabled by pairing a bank with itself and expecting a ratio of unity.
- Two decades ago, when less-reliable stepping motor systems were pushed to their limits, the times of various stages of an assay were less repeatable than they are today. A correction factor for such a problem was developed and is still included in today's software. Its main use is to check on the repeatability of the times, which are so reproducible that the correction factor is close to unity. If the correction factor is within, say, 0.5% of unity, the correction is set to unity. The actual limit is set by the user in "General Parameters." If the correction factor exceeds the limit, it is applied as calculated and the user is notified. In practice, the correction factor remains near unity quite reliably. One shuffler, after several years of use, made about a 1% change as wear and tear made small changes in timing, and then became stable again. A sudden, large change in the correction factor from unity should stimulate an investigation into the electromechanical system to find the cause. To my knowledge, this has never occurred.
- The proximity switch for the turntable is used to verify that the turntable is turning.

E. Calibration

The shuffler measures a count rate of delayed neutrons and we must know how to convert that to fissile mass (^{235}U, ^{239}Pu, etc.). We can tell the shuffler's computer how to do the mathematics for us, but we have to figure it out ourselves first.

The best way to determine the calibration is to measure physical standards in the shuffler that accurately represent the items to be measured. The standards ideally match the items to be measured in all relevant respects (materials, size, shape, density, mass, isotopics, packaging, moisture content, and matrices). Standards usually have to be certified, meaning that the procedure used to fabricate the standards is accepted by regulatory agencies and a paper trail follows the standard to show how the procedure was followed. Sometimes such ideal standards exist, sometimes they can be made (the Billet and Liquid Raffinate shufflers had excellent standards created for them), but many times they do not exist and never will be made because of variations among the items (contents of waste drums often have this problem). An alternative approach using calculations will be discussed below.

1. Matrix Issues

The matrix is all the material in the item except the fissile material you want to measure. If you want to measure ^{235}U, then the oxygen in U_3O_8 is part of the matrix. Even the ^{238}U and other uranium isotopes are matrix material. The moisture and any other contaminants mixed with the U_3O_8 are matrix materials, as is even the container that holds the U_3O_8. If the can is inside a drum held in place by fiberboard spacers, add the spacers to the matrix. If the drum is inside an overpack, the overpack is matrix material.

Some matrix materials are benign to the shuffler's assay, but others affect the measured count rate in important ways. Anything with hydrogen can be important because neutrons lose big fractions of their energies when they scatter off hydrogen (think of the collision of two billiard balls). As hydrogen-bearing matrix is added near the fissile material, the count rate first goes up because the lower-energy neutrons induce more fissions. But as much more hydrogen is added, the count rate can go down as neutron captures in hydrogen compete with fissions. The impact on the fissile material varies with the position of the fissile material with the hydrogenous matrix, making the count rate vary with position[3].

A matrix of iron is much more benign because neutrons scatter without losing much energy (think of a table-tennis ball bouncing off a bowling ball), although some energy loss occurs and iron will absorb low-energy neutrons. With 465-lbs. of iron in a 55-gallon drum, the count rate was reduced by 4.5% compared with an empty drum,[3] a small but nonnegligible fraction.

Techniques have been developed to mitigate the effects of hydrogen in 55-gallon drums where the effects can be large simply because there is more room for matrix material than in small cans.

The original technique used flux monitors built into the side of the assay chamber. These were low-efficiency ^3He tubes whose outputs were counted during the irradiations by the ^{252}Cf source. They counted a small fraction of the neutrons that came directly from the ^{252}Cf source, a larger fraction of neutrons that scattered off the moderating walls, and another large fraction of neutrons that entered the drum and returned with reduced energies. It is these last neutrons that we really want to count; the others are unavoidable background. One of the flux monitors was wrapped in cadmium to absorb low-energy neutrons, making it rather insensitive to the matrix in a drum. The other flux monitor's count rate changed significantly with the amount of hydrogen in the drum. The ratio of the flux monitors is independent on the ^{252}Cf source strength and can be used to correct for the hydrogen.[3]

A hardware solution is to envelop the drum with about 0.75 in. of polyethylene. A sleeve made from a septic tank liner fits around a 55-gallon drum very nicely; adding a top and bottom completes the envelopment. The result is a huge reduction in an otherwise large variation in count rate with the position of the fissile material. This happens because the first one or two collisions happen in the external polyethylene, reducing the range of energies of the neutrons entering the drum. The effect the matrix has on the neutrons is greatly reduced by the sleeve.[3] The calibration no longer has to deal with changing count rates with position within the matrix.

However, a polyethylene sleeve increases the self-shielding problem because the neutrons' energies are lower. If the drum contains waste quantities with small particle sizes, this is not an important issue. But if large pieces are present, the assay will be biased low by the self-shielding. A second technique has been developed for this case.

If the positions of the uranium in a drum can be determined, a matrix correction factor can be applied to each piece of uranium that is appropriate for that position. This technique, developed for the standard 55-gallon drum, does not require any extensive modification to the hardware. A stepping motor must be used for the turntable instead of an analog motor, but this is not a difficult task. The Compumotor Indexer Model 4000 can drive four motors, so even this module needs no change. The software needs extensive modification because the collection of data and its analysis is quite different from the conventional shuffler assay.

Six detector banks around the sides of a 55-gallon drum, plus banks above and below the drum, are used to give a low-resolution (≈10 cm) "picture" of the distribution of fissile material within the drum. The drum does not rotate during a set of irradiation and counting shuffles. The count in a bank depends on the relative positions of the ^{252}Cf source and the fissile material to that bank. To get enough information to locate the material, the drum is rotated 60° and another set of shuffles is done. This is continued for a full revolution of the drum. The mathematical algorithm is then applied to calculate the amount of fissile material in each of the 39 (or so) cells of equal volume within the drum. This algorithm uses calibration data from measurements on a standard placed sequentially in each of the 39 (or so) cells. It is not necessary that the matrix be homogenous, as is usual with the conventional shuffler measurement procedure, only that it is known and the calibration drum accurately reflects the distribution. The count time is approximately doubled with this technique, but this only means going from 15 min. to 30 min.

For many matrices, there is no need to make a matrix correction. Cans of high-fired oxide have a rather benign and constant matrix (oxygen, steel walls) and what minor effects arise are automatically included in the calibration. Uranium carbide has an important matrix component (carbon), but it, too, is present in fixed relations with the uranium and can be included in the calibration as long as the geometric form is fixed. Each measurement should be analyzed for matrix effects and the most appropriate way to handle matrix problems.

2. Calculated Calibrations

What are the options for materials that do not have calibration standards? The creation of new, certified standards is expensive and time consuming—a set of six U_3O_8 standards with 0.5 to 4.0 kg of uranium from the National Institute of Standards and Technology (NIST) cost $100,000 in 1999). If the items of interest are unique, it makes little sense to create a standard and double the inventory size. However, the calibration with U_3O_8 standards cannot be applied reasonably to U metal, UC_2, ^{233}U, ^{239}Pu, etc., because there will be large biases (Fig. 23).

Is there a way to calculate shuffler count rates and bypass the lack of physical standards? The topic can be controversial, but it can also be demonstrated to be either accurate or not. What is needed is not just a good approximate calculation, but calculated results that are as accurate as measured calibration data. This difficult goal requires great attention to detail and as much benchmarking as possible.

A computational procedure for the standard 55-gallon-drum shuffler has been developed[2] and it could be readily applied to any other shuffler. For this large assay chamber, the ^{252}Cf source usually scans vertically during an irradiation of even a small can of oxide; scanning is not necessary in all cases, but it is usually done. This means that the neutron flux entering the fissile material varies with time, greatly complicating the calculation. The situation would be much simpler if the source were stationary (as in some other shufflers), so if the 55-gallon-drum shuffler with a scanning source can be accurately described, the process will work for other shufflers.

The steps in the procedure to calculate absolute shuffler count follow.

- Create an accurate MCNP model of the shuffler, including the fissile material and container.

- For each fissile mass of a set of masses, use MCNP to calculate the fission probabilities (per ^{252}Cf neutron) at representative positions of the ^{252}Cf source. For a 30-in. scan distance, a calculation at every 2 in. has been adequate.
- Perform a separate MCNP calculation for the detection efficiency of delayed neutrons starting within the fissile material. (Do *not* use the detection efficiency measured with a weak ^{252}Cf source in an empty chamber; it will be much lower than for delayed neutrons. An AmLi source in an empty chamber will give a good efficiency for delayed neutrons in an empty chamber, but the detection efficiency for delayed neutrons escaping a container may be different because of moderation and absorption.)
- Use the fission probabilities to calculate the six-group precursor populations at the end of the first irradiation. These are the numerical solutions of six differential equations.
- Calculate the count of delayed neutrons after the prescribed number of shuffles.
- Get the count rate by dividing the count by the sum of the individual count times.
- Use the set of masses and count rates to form the calibration curve.
  This plan works and results in a reliable, accurate calibration curve result. Reference 2 provides details of the procedure and a comparison with measurements on uranium metal and oxides. Figure 24 shows measured and calculated rates for U_3O_8 calibration standards; there is no difference between the sets of calculated and the measured count rates. Similarly accurate calculations have been done for metals of uranium, plutonium, and their combination.

3. Enrichment Issues

The intent of the shuffler is usually to measure the mass of ^{235}U present, but ^{238}U is inevitably present, and because it also fissions, it adds to the delayed neutron count rate. If the enrichment is constant, the calibration curve will automatically include the effect and will give accurate ^{235}U masses (this is the case in Fig. 24 with 92.4% enrichment).

If the enrichment is a variable, two techniques have been applied to avoid biased results.

The first is a hardware technique—spectrum tailoring—that involves surrounding the ^{252}Cf source with a selection of metals to reduce the energies of the neutrons below 1 MeV. This avoids fissioning the ^{238}U except by high-energy neutrons from fissions of ^{235}U; this effect is generally negligible. The Bathtub and Savannah River Uranium Scrap shufflers used spectrum tailoring successfully to avoid the enrichment problem.

But spectrum tailoring is not always practical. The flux of neutrons into the fissile material is reduced by the spectrum-tailoring materials, but a larger mass of ^{252}Cf can almost always be used to compensate. If the source scans along a 55-gallon drum, the spectrum-tailoring metal would have to extend over the full distance (30 in.), increasing the weight and cost accordingly. If a 550-μg source is normally used, the tailored source might have to have a mass of 1000 μg or more. The size of the shuffler would have to grow at least another foot in all dimensions because of the additional personnel shielding required.

The second technique is software based. If standards exist with different enrichments, the shuffler's software can interpolate among calibration curves for different enrichments.

The best approach to the enrichment issue at a particular facility needs to be decided early in the physics design phase by considering the measurement specifications, facility installation requirements, and the practicalities of shuffler designs.

G. Shuffler Maintenance

1. Routine Maintenance

Most shufflers require only minor maintenance. There are no special routine mechanical or electrical checks that must be done to keep a shuffler running properly. Users take regular measurement control measurements and analyze trends; any problems will be revealed by these measurements.

It never hurts to check the voltages from power supplies, but in practice even this is rarely done. The electronics have been very reliable. If the shuffler is critical to continued operations, spare components can be kept on hand for quick substitution; but the failure rate is close to zero.

While not really routine maintenance, on occasion a proximity switch in the door or under the turntable has had to be readjusted because of some slight settling. The sensitivity of the switches is such that metal has to be virtually in contact with the sensor to trigger it, so an almost imperceptible shift in a door might require a small repositioning of the switch. This was called to our attention when the shuffler software refused to perform a measurement until the switch said the doors were close, so this is a fail-safe condition.

2. ^{252}Cf Source Replacement

If the precision of a shuffler is to be maintained for a given assay time, the ^{252}Cf source will eventually decay to a size small enough to require replacement. This operation can be delayed by extending the assay time or relaxing the precision requirement. A new source will be needed certainly within 10 years of use.

The process of replacing a source has already been described, so it will only be noted here that it involves wide participation from facility personnel, most notably the radiation safety people. Start working with them early to establish a procedure that will keep the doses to the workers very low (< 20 mrem).

3. Cable Lubrication

The Teleflex cable and the ^{252}Cf capsule move many times at high speed through a steel guide tube. Should the cable and capsule be lubricated? If so, how often, with what lubricant, and by what technique?

A test bed was used in 1981 to investigate these issues and a cable with a dummy capsule was tested under different conditions. The pertinent hardware was the same as is used today; high-speed runs were made repeatedly using longer distances than even the 55-gallon-drum shuffler uses (150 and 210 in. compared to 90 in.). After a long-term test of 1,700,000 shuffles (back and forth) there were no failures and negligible wear on the components. If a normal assay has 34 shuffles, this test is equivalent to doing 50,000 assays. This represents about 10 years of full-time use of a shuffler; obviously the equipment could be used for much longer.

The Teleflex cable is manufactured with lubrication already embedded in it, but it is minimal and does not leave a noticeable trace on hands and fingers. Additional lubrication should be applied to alleviate wear on the cable after years of use. Applying motorcycle chain oil before the source is installed has proved adequate. To apply it, dampen a rag damp with a small amount of oil and pull it along the cable once. It is not practical to lubricate the ^{252}Cf capsule without needing some extensive equipment. Because the guide tube receives a thin film of oil from the cable, the capsule will get some of this lubricant. When a new source is installed, it is simplest to use a new cable, and that is the logical time to introduce oil on the cable.

More complicated schemes have been followed, but not always successfully. Oil can be applied to a cable through the openings above the proximity switches, but this is not recommended, and it is certainly not a good idea to squirt oil into these openings. If is seems necessary to apply oil through these openings, use a rag or brush and a small amount of oil.

Using a different type of oil without thoroughly cleaning the tube and cable first will likely lead to trouble because the oils may react with each other and hinder the motion rather than help it. A complete cleaning or replacement of the tube and cable will then be required.

4. Desiccant Changing

In some installations, the desiccant for the ^{3}He tube junction boxes never needs to be changed because the humidity is always low. But in high-humidity areas, desiccants are clearly important. They can be examined from the outside to see if they need to be changed; a color indicator on their tops shows the current humidity level inside. A facility has to gain experience over a year or two to know if capsules need to be changed and how often. Changing a capsule is a simple matter of unscrewing an old one and screwing in a new one.

The desiccant material is reusable, in theory. It is not expensive, but it can be dried in a microwave oven (take it out of the metal capsule first).

V. DATA ANALYSIS

The assay chamber is the heart of the hardware and the data analysis is the heart of the software. Everything about a measurement comes together in the data analysis.

A. Raw Count Rates

Background counts are taken at the start of a measurement and counts are taken after each irradiation. These are the “raw” counts that are converted into “raw” count rates by using the measured times (from channel zero of the 12-channel scaler).

Times differ slightly from the specified or nominal values because the computer’s timer is used to control the 12-channel scaler. The scaler’s channel zero scaler is precise to 0.001 s, but the computer’s timer is not as precise. The actual variations in repeated time intervals is very small and of no practical importance. If the 12-channel scaler could be read “on the fly,” the times used would be even more accurate, but assay results would not be improved.

1. Background Counts

Before a background count is taken, the software ensures that the ^{252}Cf source is in the store position. Leakage of ^{252}Cf neutrons into the assay chamber increases rapidly as the source approaches the assay chamber, so it is important to put the source in a standard position where it contributes only a few counts a second. About a fourth of the assay time is spent on the background count. If the background is dramatically higher or lower than usual, the background count time should be changed to optimize the precision of the assay result. Background count rates are calculated from the counts and the measured background count time.

Whether or not a background count is necessary at the start of each measurement can vary among shuffler applications. If drums of scrap metal and drums of paper are to be assayed, there will be different background rates because scrap metal interacts with cosmic rays to produce neutrons. If the shuffler always measures the same type of material in a stable environment, a single background rate might be applied to assays. But to cover all cases, the standard software takes a new background count at the start of every measurement.

2. Flux Monitor Counts

If flux monitors are present, they produce counts during the irradiations even if the counts are not going to be used in the data analysis. The irradiation times are measured and used to calculate flux monitor count rates.

3. Postirradiation Counts

These counts are from both background neutrons and delayed neutrons. The signal (delayed neutron counts) is here, but not yet extracted into a useful value. None of these counts are corrected for dead-time losses because the count rate are always very low (e.g., under 10,000 counts/s).

B. Background Subtraction

The uncorrected delayed neutron count rate is extracted from the postirradiation count rate by subtracting the background count rate. The background rate for the inefficient flux monitors is usually zero and is always negligible compared to their very high count rates.

C. ^{252}Cf Decay Correction

The ^{252}Cf has a lower neutron yield each day and if this were not taken into account measurements on the same item would be smaller each day. This is easily avoided by adjusting the measured delayed neutron count rate for the decay following some convenient reference date. The reference date might be the date the source supplier measured its yield, the date the source was installed, the date on which the first calibration was done, or any other date. The best value we have for the decay constant is $7.172\text{x}10^{-4}$ d^{-1}. A year after this reference date, the delayed neutron count rate will be multiplied by 1.2995 to adjust for the decay; after 5 years, the multiplier is 3.7062. The half-life of ^{252}Cf is known well enough to make this calculated correction accurate for the useful life of the source.

No adjustment is included for ^{250}Cf neutrons because sources are not used more than 10 years and the number of ^{250}Cf neutrons is negligible compared with neutrons from ^{252}Cf, even through 20 years of decay (Fig. 20).

D. Cycle Irregularities Check and Potential Correction

As mentioned before, the electromechanical system is very repeatable and reliable, so variations in the times spent on various stages of an assay are minor and of no consequence. But larger variations could be important and should be detected if they occur. Rather than compare individual times with some expected values, all the times are combined in the same way that they impact the count of delayed neutrons. This overall result is compared with the result using the expected times. If the ratio deviates from unity by some preset fraction (e.g., 0.5%), the user is notified that there has been an unusual occurrence.

If the ratio is within acceptable limits, no correction for cycle irregularities is applied. Otherwise, the ratio multiplies the measured count rate and modifies it to make it seem to have come from the standard assay stages. This correction is not recommended for routine operation. If the ratio is far from unity, it should be readjusted or some electromechanical problem fixed.

E. Flux Monitor Matrix Correction

If hydrogenous matrices are involved in assays, the flux monitors might be used to correct for different amounts of hydrogen. The ratio of the flux monitor counts is a measure of the hydrogen content, but the exact relationship depends on the complete nature of your materials and the shuffler design. A series of measurements on standard containers needs to be done to reveal the relationship and then it can be built into the shuffler software.

Flux monitors are not needed if the matrices are not hydrogenous, if calibrations have been done for amounts of hydrogen that will be encountered, or if the position-correction style of assay is used.

F. Unique Corrections

Specialized shufflers may have unique corrections that are not part of the standard software package. For example, the Liquid Raffinate Shuffler gave different count rates according to the flow rate of the liquid. A higher flow rate gave a lower count rate because a fixed amount of uranium received less irradiation and had less time to provide delayed neutrons. The flow rate was measured with a flow meter and the information sent to the shuffler's computer.

The Spent Naval Fuel and Dounreay shufflers were designed to control hoists that passed long items through the assay chamber. With the same speed for every assay, there was no need to correct for different speeds. But if a similar measurement were not so well controlled, a correction would be needed for the deviation from the speed used for calibration. None of these or other unique corrections is included in the standard software package.

G. Normalization

At this point in the data analysis, the corrected measured count rate is normally ready to use with the calibration to give a fissile mass. However, the software provides one last chance to apply a correction for some unusual circumstance. To my knowledge, this has never been needed, but it might be helpful some day. For example, assume that one tube out of 64 has failed. The measured count rates will all be low by about 1.5% and the assay result will be biased low by about the same fraction. This could bring the shuffler use to a halt until the tube is replaced. If a spare tube is not on hand, it could take three months to get a new one.

To keep the shuffler operating properly under such a condition, a normalization factor can be applied to the corrected count rate just before using the calibration curve. If one tube is out, the count rate can be multiplied by about 1.0152 to simulate a full set of operating tubes. The multiplier will probably be different if the defective tube is in a side bank or an end bank because they have different lengths.

The best normalization factor could be found by measuring a known item. This might be a passive count of a ^{252}Cf or AmLi source that had previously been measured, or it might be an assay of one of the calibration standards. Fortunately, the normalization factor for any shuffler has never been anything but unity, and the hardware has proven to be quite reliable.

H. Calibration Curve

The object of an assay is finally achieved when the corrected count rate *r* is used to calculate a mass of the fissile material *m* using a calibration curve. The only form for the curve in the standard software package is this third-order polynomial with *r* expressed as a function *m* (as preferred by statisticians):

$$r = a_0 + a_1 m + a_2 m^2 + a_3 m^3 .$$

It is easy to substitute any other curve for this one but that has not yet been necessary.

Waste materials are likely to have only a_0 and a_1 nonzero. Measurements of oxides and metals up to 8 kg have been very well described by this polynomial. However, the software is written to invert any expression for the mass using a numerical rather than an analytical process, so if another calibration expression is preferred it is easy to implement.

The four coefficients are determined from measurements on physical standards or from carefully calculated absolute count rates. They have a set of variances and covariances that can be specified and used to help calculate the uncertainty in a mass.

Figure 24 shows a calibration for U_3O_8 standards up to 8 kg. Self-shielding is evident for the first 750 g and then the curve becomes linear. The standards with masses of 3600 g or less are certified accurate; the higher masses are less certain.

The statistical uncertainties in the various counts are calculated by the software and combined with the calibration's variances and covariances to generate a total uncertainty (1σ) in the measured mass. In practice, the variances and covariances usually dominate the uncertainty[9], so careful and extensive measurements of calibration standards can have beneficial effects on the quality of future measurements.

I. Bias Correction

Another software option that is provided (but never used, to my knowledge) is a bias correction factor after the mass has been calculated. If there is a known bias in the calibration coefficients, it is usually best to correct the calibration coefficients. But a postcalibration bias correction would be preferable if, for example, the interior of the assay chamber were contaminated with nonremovable uranium. In that case, an "empty" assay chamber might give an assay result of something like 1.3 g instead of zero. The bias correction could be used to subtract 1.3 g from all other uranium measurements.

The bias correction might be used to maintain the shuffler's throughput until the contamination is removed. It is possible that the correction could be affected by the item being measured. In the contamination example, the empty-chamber measurement may give 1.3 g, but this same uranium will experience a different neutron flux with an item present. So the bias correction may be only approximate and the best practice is to avoid the need for a bias correction.

J. Self-Checking

As was mentioned earlier, every assay includes some internal checks that can flag many hardware problems that would affect the assay result. They are restated here briefly because they are important in giving confidence in measured masses.

A wide range of hardware problems will be detected by one or more of the following checks:

- If any detector bank gives zero counts, it is assumed that there is a problem and the measurement is aborted.
- Expected values and uncertainties of ratios of counts among pairs of detectors can be preset; a ratio outside these limits generates an error message.
- The times used to move the ^{252}Cf source are compared with expected times through the use of a standard expression for shuffler count rates;[1] if these two expressions differ by more than some preset fraction (typically 0.5%) an error message is generated.
- The motion of the turntable is checked periodically by watching the turntable's proximity switch toggle once per revolution.

REFERENCES

The bibliography at the end of this report contains a complete list of references to specific Los Alamos shufflers and related materials. The following references have unique importance and were called out in the text.

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APPENDIX A

Self-Shielding

During active neutron assays (e.g., shuffler, AWCC), some of the neutrons irradiating the fissile material induce fissions. As the mass of the material grows, the count rate per gram decreases; this is the "self-shielding" effect. But why does this happen?

Neutrons with high energies are less affected by self-shielding than neutrons with low energies. In particular, thermal neutrons are the most affected because they have the lowest energies. Thermal neutrons induce fissions near the material's surface while high-energy neutrons are more likely to penetrate further. The example in Fig. A-1 is a bit simplified; there is no sharp boundary between where fissions occur and where they are unlikely. The boundary shown can represent the 1/e transmission point, or some other such value.

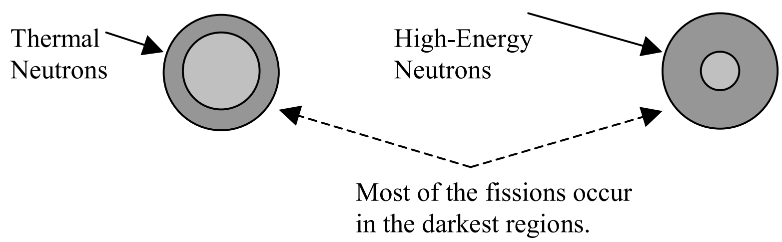

Fig. A-1. A sphere of fissile material receives either thermal or high-energy neutrons. Fissions occur near the surface with thermal neutrons, but more nearly uniformly throughout the volume with high-energy neutrons. The sharp boundaries shown here are simplifications, but illustrate the different depths of penetration where fissions occur.

But if the same number of fissions occurs with thermal and high-energy neutrons, just in different locations within the material, why is there self-shielding? The irradiating neutrons are not being prevented from inducing fissions. In the limited, simplified example of the figure above, there is no self-shielding problem just by changing the energies of the neutrons. The same number of fissions is induced within the same mass of fissile material.

Self-shielding arises from changing the mass of the fissile material for a given neutron-energy spectrum. Figure A-2 shows two widely different masses. The neutrons are able to penetrate almost the entire volume of the smaller mass, but hardly ever reach the interior of the larger mass. Nevertheless, about the same number of fissions per gram of fissile material occurs in the two darker regions.

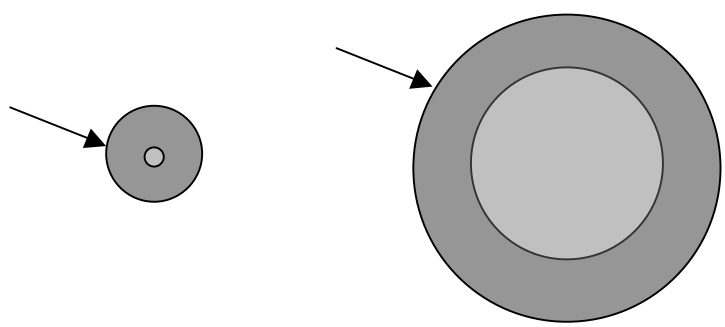

Fig. A-2. Spheres of different sizes receive neutrons with the same incident energy. Fissions take place at the same depths, but much of the larger sphere is never reached by the neutrons because the outer portion shields the inner portion. This is self-shielding.

The number of fissions per gram of the total fissile material present is quite different for these two objects. Much of the material in the larger object has no fissions; it contributes to the mass of the object but not to the fission rate. The fission rate per gram is less than it is with the smaller object. The outer portion of the larger object shields the inner portion from the neutrons; it has done this to itself, so it is "self-shielding."

This concept can be given a quantitative analysis. Figure A-3 shows a sphere irradiated in two ways. It is artificially assumed that all fissions occur in the "skin" of a given thickness. In either case, the fission rate is proportional to the square of the radius because the cross sectional area is πr^2 in the first case and the surface area is $4\pi r^2$ in the second case.

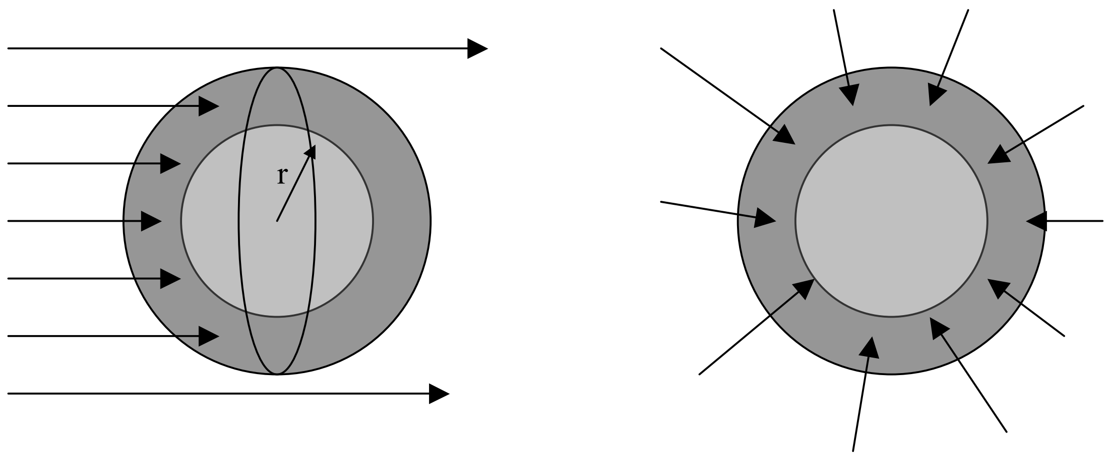

Fig. A-3. The same sphere is irradiated by either a parallel beam of neutrons (left) or neutrons converging toward the sphere's center (right). The fission rate is proportional to the cross sectional area of the sphere in either case.

The count rate c from spheres is $k_1 r^2$ for all manners of irradiation. The mass of the fissile material is proportional to the cube of the radius: $m = k_2 r^3$. The count rate is related to the mass by $c = k_3\ m^{2/3}$. This is a power-law expression $c = a\ m^b$. The slope decreases as m grows: $dc/dm = k_4\ m^{-1/3}$. The slope seems to be infinity at m=0, but this analysis only applies to masses large enough to have the full thickness of absorbing skin shown in the diagrams. The smallest applicable radius is the thickness of this skin.

A calibration curve without self-shielding would be a straight line. The count rate *c* would be directly proportional to the fissile mass *m*: c = k m. But self-shielding makes *c* less than this expression predicts, particularly as *m* gets larger. The power law suggested in the preceding paragraph is not always the most accurate way to describe the data because the simple assumptions made here are rarely met. For example, with a broad spectrum of neutron energies, the skin thickness is a rather fuzzy concept. There are also neutrons released inside the material by the fissions and these can penetrate further into the material and induce a new generation of fissions. But the mathematical expressions used are not very different from a power law in shape. Second- or third-order polynomials (e.g., $c = a_1\ m + a_2\ m^2,\ a_2<0$) are often used, as is $c = (a\ m)/(1 + b\ m)$.

The graph in Fig. A-4 is a visualization of self-shielding; the numbers are meaningless, but serve to illustrate the concept. The upper curve, a straight line, shows no self-shielding. The lower curve showing self-shielding deviates from the straight line more and more as the mass grows.

This analysis has used spheres. This is likely to represent powders (U_3O_8, PuO_2) rather well. But what if the fissile particles were flakes (flat particles with one dimension much smaller than the other two)? If the smallest dimension is smaller than the absorption thickness and the flakes were distributed without stacking upon each other, there would be little or no self-shielding regardless of the size of the flakes. But this case does not seem to arise.

Self-shielding is greatest when low-energy neutrons are irradiating a large object. By keeping neutron energies as high as possible, the depth of penetration is increased and self-shielding is reduced. There will generally be a reduction in count rate because high-energy neutrons are less likely to cause fissions. Self-shielding and fission rates are coupled and improving one of them harms the other.

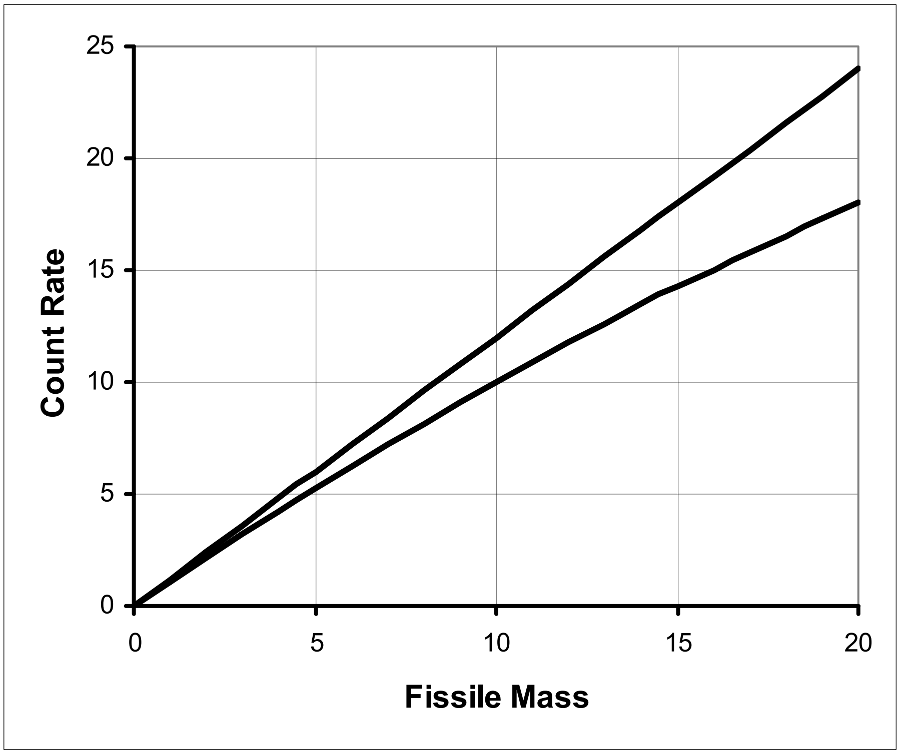

Fig. A-4. The upper curve is a straight line and represents the case with no self-shielding: the count rate is directly proportional to the fissile mass. The lower curve shows the reduction in the count rate caused by self-shielding and it is nonlinear.

Self-shielding is responsible for an important effect in neutron active assays. The count rate from 1000 g-^{235}U in one lump is less than the sum of the count rates of two 500 g-^{235}U lumps when measured together but physically separated. Cans of oxide make another good example (Fig. A-5).

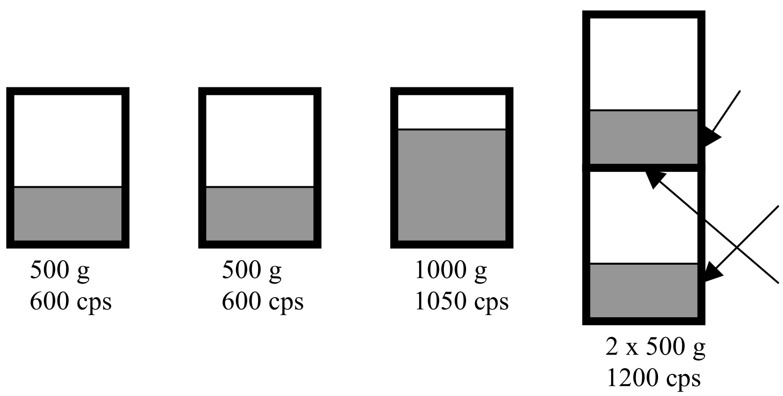

Fig. A-5. Cans with different amounts of UO_2 are illustrated. Representative count rates are assigned to each can. Because of self-shielding differences, two cans stacked vertically are not equivalent to one can with a the same mass of UO_2.

On the left of Fig. A-5 are two identical cans, each with 500 g of fissile material. They give identical count rates of 600 cps. The 1000 g gives less than 2x600 cps because of self-shielding. Stacking the two 500-g cans as shown on the right gives 1000 g and 2x600 cps because there is hardly more self-shielding than with a can with 500 g. The gap between the two 500-g portions allows neutrons to penetrate the materials more easily than with 1000 g. Neutrons are somewhat like a gas in that they flow into all regions through multiple scattering. This shows that a calibration curve will be confused by stacking such cans together.

However, the situation is different for metal disks (not packaged in cans). They can be stacked without any gaps and the stacking would be appropriate for generating data for a calibration curve. Figure A-6 shows metal disks individually and as a stack of three. The self-shielding is the same for a single 300-g mass and three 100-g masses because they fit tightly together. The count rate with 300 g is not 3x200 = 600 cps because of self-shielding, but the self-shielding is the same for both objects with 300 g.

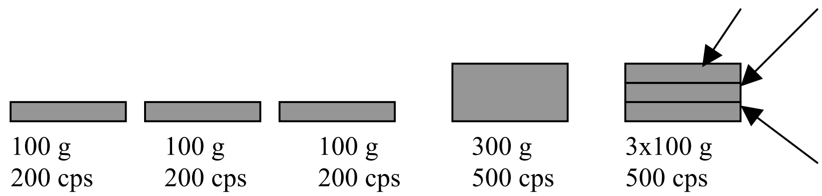

Fig. A-6. Uranium metal disks are shown edge on. Those at Los Alamos have diameters of 6 cm and heights of 1 cm. Three of these disks are shown on the left; they give identical individual count rates in a shuffler. On the right, these disks are stacked and compared with a single disk with the same mass as the stack. These two ways to form a 300-g disk are physically identical and give the same count rate. There are no gaps that change the self-shielding in the two cases, as in Fig. A-5.

APPENDIX B

Multiplication

When a neutron from the ^{252}Cf source of a shuffler induces a fission in the material being assayed, that material releases additional neutrons. The average number of these neutrons from ^{235}U is about 2.5; from ^{239}Pu it is about 2.9. Most of these neutrons are "prompt" and are released at the same time as the fission. They are not delayed neutrons and are not counted by a shuffler.

But prompt neutrons (and delayed neutrons) can induce further fissions in the fissile material beyond those induced by the ^{252}Cf source. These second-generation fissions release even more prompt and delayed neutrons. The result is a larger count rate than would result from fissions caused only by the ^{252}Cf source alone. The measured count rate is the simple count rate *multiplied* by some number (the multiplication factor) greater than one. Multiplication of neutrons has occurred, including the delayed neutrons. (If there is no multiplication, the multiplication factor is unity.)

The phrase "leakage multiplication" is used in passive neutron counting and also applies to shufflers. This focuses the attention on only those neutrons that escape the fissile material and enter the detection region of an instrument. Leakage multiplication ignores those neutrons that are created by a multiplication event only to be absorbed within the fissile material and therefore have no effect on the measured count rate.

For a 5-inch diameter can with 500 g of ^{235}U in UO_2 with 93% enrichment, the multiplication factor is about 1.035. The diameter of the can affects multiplication because a shape of the fissile material closer to a sphere will induce more second-generation fissions. There are other parameters that can affect multiplication: the moisture content, the closeness of the assay chamber walls to the can, a cadmium liner of the assay chamber, and neutron absorbing impurities within the can.

The Monte Carlo code MCNP offers help with calculating multiplication. In the "creation/loss ledger" a "net multiplication" is given; call it M_{MCNP}. From the definition of M_{MCNP} given in the manual, this is identical with the "leakage multiplication" that we use.

$$M_{MCNP} = \frac{1 - k_{eff} / \bar{v}}{1 - k_{eff}} \quad . \tag{B-1}$$

The value of $\bar{V}$ can be estimated by the ratio of "fission neutrons" to "fission loss" as given in a MCNP output file's Table 130 called "neutron weight balance in each cell."

MCNP also has a "k-code" feature that generates k_{eff}. The "true multiplication" is $M = 1/(1-k_{eff})$, but this is concerned with all the neutrons produced by the fissile material instead of only those that leak into the detection region.

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